ANNALS

OF THE

ASTROPHYSICAL OBSERVATORY

OF THE

SMITHSONIAN INSTITUTION.

VOLUME II.

By C. G. ABBOT, Director,
and
F. E. FOWLE, Jr., Aid.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
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PREFACE.

The Astrophysical Observatory of the Smithsonian Institution was founded through the efforts of the late Secretary Langley, who was its Director until his death. The research described in the present volume is a continuation of the work on the relations of the sun to climate and life upon the earth, of which he was a brilliant pioneer investigator.

Mr. Langley expressed the hope that careful study of the radiation of the sun might eventually lead to the discovery of means of forecasting climatic conditions for some time in advance. It is believed that the present volume will aid materially to show how far that hope may be justified, for it contains careful and comparable measurements of the solar radiation, extending over several years. These indicate that the sun's radiation alters in its intensity from time to time, and that these alterations are sufficient to affect the temperature of the earth very appreciably.

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ANNALS OF THE ASTROPHYSICAL OBSERVATORY OF THE SMITHSONIAN INSTITUTION.

VOLUME II.

INTRODUCTION.

ANNALS OF THE ASTROPHYSICAL OBSERVATORY, 1900–1906.

Principal investigations.—With the publication in 1900 of Volume I of these Annals, the minute bolographic study of the absorption lines of the infra-red solar spectrum was discontinued, and attention was turned principally to the measurement of the total amount of solar radiation, its intensity at different wave-lengths, and the effect of the sun's envelope and earth's atmosphere upon the transmission of the different rays of the spectrum between the wave-lengths 0.35μ and 2.8μ.

Solar-eclipse expeditions.—Before recounting the progress of this research, it may be stated that in consideration of the high interest attaching to observations at the time of a total solar eclipse, and of the near approach to Washington of the belt of totality for the eclipse of May 28, 1900, it appeared wise to undertake an eclipse expedition from the Observatory. Congress approving this view, the sum of $4,000 was appropriated specifically to defray the cost of the expedition and the publication of its results. Accordingly, the first six months of the year 1900 were spent almost wholly in the preparation and reinstallation of apparatus incidental to the expedition. Fortunately, the day of the eclipse proved fair, and the observations, almost without exception, were successful. An account of them was published in 1904, entitled "The 1900 Solar-Eclipse Expedition of the Astrophysical Observatory of the Smithsonian Institution." The most interesting results obtained were: (1) Photographs of the solar corona on an unprecedentedly large scale, showing much interesting detail of the inner corona. (2) A photograph of the region near the sun showing stars as faint as the 8.4 magnitude and indicating by the presence of several uncharted starlike objects a possibility of the existence of faint new planets. (3) Bolometric measurements by which the heat of the radiation of the inner corona was recognized. This heat proved, indeed, less than was anticipated, and the total radiation of the inner corona recognized by the bolometer was less in proportion to the total light visible to the eye than would be expected from bodies emitting radiation by virtue of a temperature lower than that of the sun, or even at the temperature of the sun itself.[1]

Anticipating a little in these Annals, the observations of possible intra-mercurial planets, and of the surprising feebleness of the bolometric effect of the radiation of the inner corona, in 1900, were considered to be so interesting as to make their confirmation highly desirable. Therefore, Mr. Langley detached Mr. Abbot, of the Observatory, to repeat these observations, with the assistance of Mr. Paul Draper, a volunteer observer, at Solok, Sumatra, during the very long eclipse of May 18, 1901. Unfortunately, clouds prevented success in either research on this occasion. The expenses of the Sumatra expedition were borne by the Smithsonian Institution.

Thus the first six months of the years 1900 and 1901, respectively, were largely devoted to solar-eclipse expeditions.

Sensitive galvanometer.—In the latter part of the year 1900 considerable time was devoted to the construction and trial of an improved sensitive galvanometer provided with an exhaustible air-tight case and magnetic shielding, and supported by a very heavy Julius suspension, itself hanging from a large iron pan floating upon mercury. The needle system of this galvanometer includes eight groups of magnetic needles, and hangs between eight corresponding pairs of coils. When perfected, it became possible in actual practice to measure with this galvanometer a current of 2×10^{-12} ($\frac{2}{1\,000\,000\,000\,000}$) amperes, although the total resistance of the galvanometer was but 1.6 ohms. Naturally, however, the necessary precautions and the difficulties encountered in using an instrument of this delicacy exceed by far those of ordinary practice, so that it is only when the refinement of the observations actually requires its use, that it becomes profitable to employ this galvanometer in connection with bolometric work.

The transmission of the solar envelope.—In 1901 experiments were made for the determination of the transmission of radiation in the solar envelope. These depend on the fact that rays from the edge of the sun's disk must pass through a longer path of absorbing material to reach the observer than rays from the center of the sun's disk, so that the sun appears less bright near its edge than at its center. A solar image 40 cm. in diameter was produced by means of a combination of two mirrors, comprising a concave mirror of 230 cm. focus and a short-focus convex mirror placed near the focal plane of the concave, and the Grubb siderostat was

[1] It was inferred, consequently, that the inner coronal radiation might be a phenomenon of "luminescence" similar to the glow discharge in vacuum tubes, rather than light emitted by incandescent particles, or sunlight diffusely reflected by particles. More recently a careful study of the matter has led to the conclusion that inasmuch as sunlight diffusely reflected from minute particles is richer than ordinary sunlight in radiation of short wave-lengths, the bolometric observations of the eclipse of 1900 are consistent with the view that the inner corona may be composed of minute particles or gaseous molecules seen chiefly by their diffuse reflection of sunlight.

used to feed this combination. Bolographs were taken with light from the center of the image and from points 95 and 98 per cent of the radius distant from the center. A comparison of these bolographs confirmed the results of earlier experiments by Langley, Vogel, and others, to the effect that the general transmission of the solar envelope increases from the violet toward the red end of the spectrum. But in the experiments of 1901 the transmission of the solar envelope was for the first time examined as far as wave-length 2μ in the infra-red spectrum, with the result that the transmission was found to be greater for the infra-red than for the visible rays. The spectrum was not sufficiently pure to allow of the investigation of the selective absorption in the solar bands and lines.

Second edition of Annals, Volume I.—In accordance with a resolution of the Senate of the United States, a report was prepared and submitted at the session of Congress in December, 1901, showing the appropriations expended, results reached, and condition of the Observatory at the time. This report contained a brief statement of the foundation, aims, results, and condition of the Observatory; an account of appropriations; a copy of Volume I of its Annals; a preliminary report of its eclipse expedition of 1900; and several statements by eminent foreign and American men of science, giving their estimates of the Observatory and its works. This report was referred in the Senate to the Committee on the Library and ordered to be printed with all its inclosures. Advantage was taken of this opportunity to correct some errors which had been found in Volume I of the Annals, and to secure several hundred copies of the new edition for the use of the Observatory.

Improvements in spectrobolometric work.—With the year 1902 was begun the practice of taking quick-speed bolographs of the prismatic solar spectrum extending from 0.45μ to 2.5μ in wave-length. These bolographs were secured on all favorable days, and care was exercised by determining the absorption of the optical apparatus employed, and otherwise, to make the ordinates of the bolographs true indicators of the relative amounts of energy at the various wave-lengths. In the work published in Volume I of the Annals, attention had been given almost wholly to recording accurately the places of small absorption lines and bands, but now the aim was rather to obtain true representations of the distribution of the energy of the solar spectrum with a view to detecting variations of it, which might have importance in determining climate.

Bolographs were taken in this year at different hours of each fine day, so that the general transmission of the earth's atmosphere, as indicated by the alteration of the heights of bolographs with differing lengths of path of the solar rays in the atmosphere, could be estimated. Attention was also given to determining the variation of the amount of solar radiation reaching the earth's surface as depending on the amount of water vapor present.

Improvements were made in the adjuncts of the bolometer used for obtaining a balance of its electrical resistances. These modifications were at first introduced only in the auxiliary rheostat figured in its original form in Plate XII of Annals, Volume I, but in 1904 all these adjuncts were placed wholly within a single small case surrounding the bolometer, as was the practice in the older design shown in Plate XII A of Volume I of the Annals. In both the separated and combined forms, however, a much improved and simplified arrangement was substituted for the elaborate ones shown in the illustrations just cited, and the convenience of operation was greatly increased. The sixteen-coil type of galvanometer, to which reference has been made, was also introduced in the ordinary bolographic work and proved more advantageous on account of its greater steadiness, due both to the greater weight and better natural astaticism of its magnetic system.

Improvements in the work on the solar image.—Experiments were continued on the transmission of the solar envelope as begun in 1901. Plans were discussed for providing a horizontal reflecting telescope for this research, with a single concave mirror of 50 cm. aperture and about 42 meters focal length, to form a solar image of 40 cm. average diameter without secondary magnification. This instrument was to be fed by some form of cœlostat or siderostat, but the actual arrangement finally adopted was not designed until the early part of the year 1903. It consists of a cœlostat with two plane mirrors, the first parallel to a polar axis rotating half as fast as the earth and reflecting the solar beam generally in the plane of the meridian; the second so mounted that it can be moved east and west or north and south. Light reflected from the first mirror can therefore be made to fall upon the second, whatever the declination or hour angle of the sun, and from thence is again reflected toward the great concave mirror, about 60 feet north.

Artificial "good seeing."—The principal defects of a horizontal reflecting telescope operated in this manner for solar work are the warping of the mirror surfaces under the action of sun heat and the "boiling," so called, of the image, due to rapidly succeeding changes in density of the air layers traversed by the beam. During the year 1902 attempts were made to partially overcome both these defects by means of a device proposed by Mr. Langley. This consisted in churning vigorously the column of air through which the rays pass so as to mix thoroughly the layers of differing density which naturally form in still air, and also to bathe the surfaces of the mirrors by streams of air so as to reduce the rise of temperature caused by the sun. Decisive and striking experiments indicating the value of this method were tried in the summer of 1902 with a smaller model of the large horizontal telescope. The tube of this model was 70 feet in length and 7 inches in diameter, and the air within was churned by means of a rotary blower which forced air in at a half dozen points along the tube and withdrew air at intermediate points. Photographs of several minutes' exposure were taken of the images of close double artificial stars, whose light passed twice through the tube, 140 feet in all. The photographs made when the air was churned were far superior to those made in still air. Visual observations confirmed the result in a striking manner, for the images viewed through the churned air were excellent, whereas those viewed through still air were distorted by varying streamers and other irregularities of form. After the success of these experiments the solar image was observed with and without "churning;" but it appeared that the "boiling" was chiefly introduced before the rays reached the cœlostat, though some improvement by "churning" in the horizontal tube was noted. Accordingly a similar tube 44 feet long was arranged to point toward the sun, so that the air in the beam could be "churned" for some distance above the cœlostat. Several observers were unanimous that great advantage in seeing resulted by "churning," but some "boiling" still remained. The conclusion reached from these experiments being that "boiling" could probably be entirely removed if the air traversed by the beam could be kept properly agitated, it was decided to employ on the larger scale a horizontal tube similar to that used in the experimental work, but to leave open the question of a tube pointing toward the sun till the great telescope was installed and tried.

"*The cheapest form of light.*"—A few experiments were made in the summer of 1902 on the relative heat and light from the radiation of the Cuban firefly (*Pyrophorus noctilucus*), two specimens of which were loaned for the purpose through the kindness of Doctor Howard, of the Agricultural Department. No heating whatever could be detected by the bolometer in the focus of a concave mirror of 50 cm. diameter, by which the radiation of the insect was concentrated. A portion of the flame of a standard sperm candle, equal in area to the bright part of the insect, gave, under the same circumstances, a bolometric effect of such magnitude that had the heat of the insect been $\frac{1}{80000}$ as great as this from the candle, it would certainly have been recognized. To the eye the insect was found to give one-eighth as much light as an equal area of the candle flame, and the actual candlepower of the insect was $\frac{1}{1600}$ candle. Not counting the portions of the radiation, both of the candle and of the insect, which were absorbed in the glass cover of the bolometer, it appeared that the insect gave light at less than $\frac{1}{10000}$ part of the expenditure of energy required for equal light from the candle. These observations, therefore, confirmed and extended the conclusions reached by Mr. Langley regarding the economy of this insect source of light, as published in his paper entitled "The Cheapest Form of Light."

Great cœlostat.—The first half of the year 1903 was largely occupied with the provision and installation of the great cœlostat, the horizontal telescope, and the tube for the latter with its air-churning arrangements. It was found necessary after preliminary trials to provide an improved system of mirror supports for the two cœlostat mirrors, and the Ritchey balanced support system [1] was introduced late in 1903 and found to give excellent results in practice. Preliminary work on the transmission of the solar envelope was done in September of that year.

Amount of solar radiation outside the atmosphere, and its possible variation.—Methods of estimating the transmission of the earth's atmosphere were perfected, and the practice of reading the pyrheliometer, or actinometer, simultaneously with spectrobolometric observations, at different altitudes of the sun, was made a part of the work of each fine day. From these observations computations of the "solar constant" of radiation outside the atmosphere were made. These results indicated a marked decline of solar radiation late in March, 1903, and this was afterwards found to have preceded a marked and general decline of temperature of the North Temperate Zone, as compared with the mean temperature of the same months for many years. Computation showed that this decline of temperature bore a reasonably close approximation to that which ought to follow a real decrease of the solar radiation as great as was indicated by the spectrobolometric work, so that attention was drawn to the possibility that the solar radiation might prove to be of notable and frequent variability, a knowledge of which may lead to improved methods of forecasting climate. The subsequent work of the Observatory has been directed chiefly toward the examination of this question.

Exhibit at St. Louis.—Early in 1904 an unusually elaborate display of the apparatus and operations of the Astrophysical Observatory was prepared for the exhibition at St. Louis. The exhibit included, with the great two-mirror cœlostat already referred to, a telescope and Rowland grating, both fed by the cœlostat and producing upon the walls of a darkened room a large image of the sun, often showing sun spots, and a brilliant spectrum extending round the room. There was also a bolometric apparatus arranged to produce a considerable deflection by the radiation of the observer's hand. Charts and books illustrating the work of the Observatory were included in the exhibit, and a large number of pamphlets descriptive of the work were distributed.

Work of 1904.—During 1904 observations for determining the "solar constant" of radiation were made, when possible, on all promising days. It was strongly felt by Mr. Langley, however, that no great reliance could be placed on the unsupported evidence of "solar-constant" determinations made at any sea-level station, owing to the uncertainty of the estimate of the losses in the earth's atmosphere. Furthermore, the days when apparently good results were obtained were extremely few, because the appearance of clouds or smoke is in Washington so common that it is rare that the interval of time necessary for a considerable change in the altitude of the sun does not include very apparent alterations in the transparency of the air. Mr.

[1] Astrophysical Journal, vol. 5, p. 143, 1897.

Langley had, therefore, in 1903 obtained the sanction of Congress for observations at high altitudes, with a view to collecting apparatus in duplicate to that in use at the Observatory in Washington, so that an expedition could be sent to a high and cloudless station where "solar-constant" observations could be made for several months without hindrance from adverse atmospheric conditions. Accordingly apparatus, including a new and improved spectrobolometer with all necessary appurtenances, a two-mirror cœlostat of 15 inches aperture, and a standard pyrheliometer of entirely new design, was ordered or constructed at the Observatory shop in preparation for the proposed expedition.

Examination of the great solar image to note changes in the transmission of the solar envelope was still prosecuted as opportunity offered, though interrupted by the exhibition of the great cœlostat at St. Louis, and by the erection of wooden and canvas shelters (covering, respectively, the cœlostat, concave mirror, spectrobolometer, and tube of the horizontal telescope). By the end of the year all these adjuncts were in order so that the observations of solar transmission began to be made as often as the absence of clouds would permit. In this work, unlike the "solar-constant" work, it is not required that the air shall remain of uniform transparency for any considerable length of time. Hence many days which would be unsuitable for determinations of the solar radiation are satisfactory for estimating the solar transmission. It would naturally be expected that diminished solar radiation would be attended and caused by decreased solar transmission; therefore it was hoped that the observation of the great solar image might confirm and at length supplant wholly the work of determining the "solar constant."

Mount Wilson expedition of 1905.—Early in the year 1905 an invitation was extended to Mr. Langley by Professor Hale, director of the Carnegie Solar Observatory on Mount Wilson in California, to send the proposed "solar-constant" expedition to that station. The invitation was one result of Mr. Langley's original suggestion, in 1902, to the then recently founded Carnegie Institution, that it might profitably establish at a high and choice station a solar observatory, charged, among other aims, with the frequent and accurate determination of the "solar constant" of radiation. When the Carnegie Solar Observatory became established on Mount Wilson, Professor Hale, knowing that a Smithsonian expedition to a high station was proposed, stated to Mr. Langley that he felt that the readiest and best means of beginning this work would be for the proposed expedition to take station on Mount Wilson, and he offered all the facilities which his previous occupation had made available to further the objects of the expedition. The question of continuing the work was left open, to be decided after observations there had been begun. As regards cloudlessness, absence of wind, and excellence of seeing, the station was declared to be ideal; and though not so high (6,000 feet) as Mr. Langley would have preferred, it was thought best to accept Professor Hale's kind offer and, if the results should seem to require it, to use Mount Wilson as a base from which to send a temporary expedition to Mount Whitney or some other high peak in California.

Accordingly the first four months of 1905 were largely occupied with preparing for the Mount Wilson expedition. A complete outfit in duplicate of the one customarily used in Washington was gotten ready, for it was decided to have the work both on the solar radiation and the solar transmission carried on as usual at the Smithsonian Observatory. It happened, fortunately, that the U. S. Weather Bureau, then erecting its new observatory at Mount Weather, Virginia, where it was proposed to take up spectrobolometric work, desired to have one of its observers trained in the methods employed at the Smithsonian Institution. Thus, by acceding to the request of the Chief of the Weather Bureau, an assistant was at the same time secured to aid in the work during the absence of one of the Smithsonian Observatory staff. An additional assistant was engaged temporarily to take part in the observations on Mount Wilson.

The apparatus, packed for mountain transportation, left Washington in April, and the observers reached the station May 10, 1905, where much of the equipment was found already arrived. Two shelters, with piers, were soon erected for the spectrobolometer and the new standard pyrheliometer, respectively, and observations were begun with the mercury pyrheliometer May 12 and with the spectrobolometer June 5. "Solar-constant" observations, occupying from five to eleven hours a day, were made as often as twice or more each week and continued up to the end of October. There was such a complete freedom from cloudiness that the programme could be laid out for each week with practical certainty that the weather would interpose no hindrance. On a number of days spectrobolographic examinations were made of the solar envelope, and in sun spots, as observed on the solar image of the Snow horizontal telescope of the Carnegie Solar Observatory.

Toward the close of August, simultaneously with pyrheliometric and spectrobolometric work on Mount Wilson, the pyrheliometer was read for two days on Mount San Antonio, a mountain over 10,000 feet high and about 25 miles to the eastward of Mount Wilson. Among other pieces of miscellaneous work, on several different days during the stay on Mount Wilson, the radiation scattered at different angles from the sky, and from clouds of fog, was compared in intensity with the direct beam from the sun.

Washington observations of 1905.—Throughout the year 1905 the observers in Washington continued to measure the transmission and radiation of the sun whenever the weather would permit. Thus it was hoped to obtain evidence of two wholly independent kinds from stations separated by 3,000 miles in distance and 6,000 feet in elevation, which would certainly decide the question whether the sun varied appreciably in its emission of radiation during the six months from May 1 to November 1, 1905.

Death of Mr. Langley.—On February 27, 1906, the Observatory lost by death the services of its first Director, Samuel Pierpont Langley, one of the foremost among the founders of the science of astrophysics and a man singularly able in originating and pushing forward astrophysical researches of the first rank. A distinguishing characteristic of his directorship of the Astrophysical Observatory was this: That while interested in all researches for the advancement of knowledge, he took the strongest interest in those studies likely to be of material utility. It was ever his aim that the investigations of the Astrophysical Observatory should have this as their ultimate object. He hoped that the study of the sun might eventually lead to improved methods of forecasting climatic conditions and that a more complete knowledge of the amount and possible variation of solar radiation and the effects produced upon it by the atmosphere would promote especially the art of agriculture.

Renewal of Mount Wilson expedition.—At the request of the director of the Carnegie Solar Observatory and the president of the Carnegie Institution, nearly all of the Smithsonian apparatus used on Mount Wilson in 1905 was left there during the winter, that the work might go on again in 1906, and by invitation of these gentlemen the Smithsonian expedition was renewed in May, 1906. The chief object in view was to continue the observations for determining the solar radiation outside the earth's atmosphere, to confirm the suspected variability of the sun. Improvements were made in the equipment used for this purpose, and there was also provision made to measure the reflecting power of clouds and sky at all angles of incidence. For this purpose a tower was built on a point overlooking on three sides deep canyons which are occasionally filled nearly or quite to the base of the tower with level clouds of fog.

Washington observations of solar radiation and transmission were continued in 1906 as before.

The Mount Wilson expedition of 1906 continued the observations of solar radiation until October 23, 1906, when the apparatus was packed and partially returned to Washington. Mr. Abbot, in charge of the expedition, was assisted for three months by Mr. L. R. Ingersoll and occasionally by members of the staff of the Carnegie Solar Observatory. Thanks are due also to Mr. J. Evershed, who aided in the observations on several days during his stay on Mount Wilson.

Personnel.—During the years 1900 to 1905, inclusive, the permanent scientific staff of the Observatory remained as given in Volume I of the Annals, namely:

S. P. Langley, Director.
C. G. Abbot, Aid Acting in Charge.
F. E. Fowle, Junior Assistant.

Mr. Langley's death occurred on February 27, 1906.

Mr. Abbot became Acting Director on July 1, 1906, and succeeded to the post of Director on March 1, 1907.

Mr. Fowle's title was altered to Aid on April 1, 1907.

There have been engaged in the scientific service of the Observatory for periods of less than six months the following gentlemen:

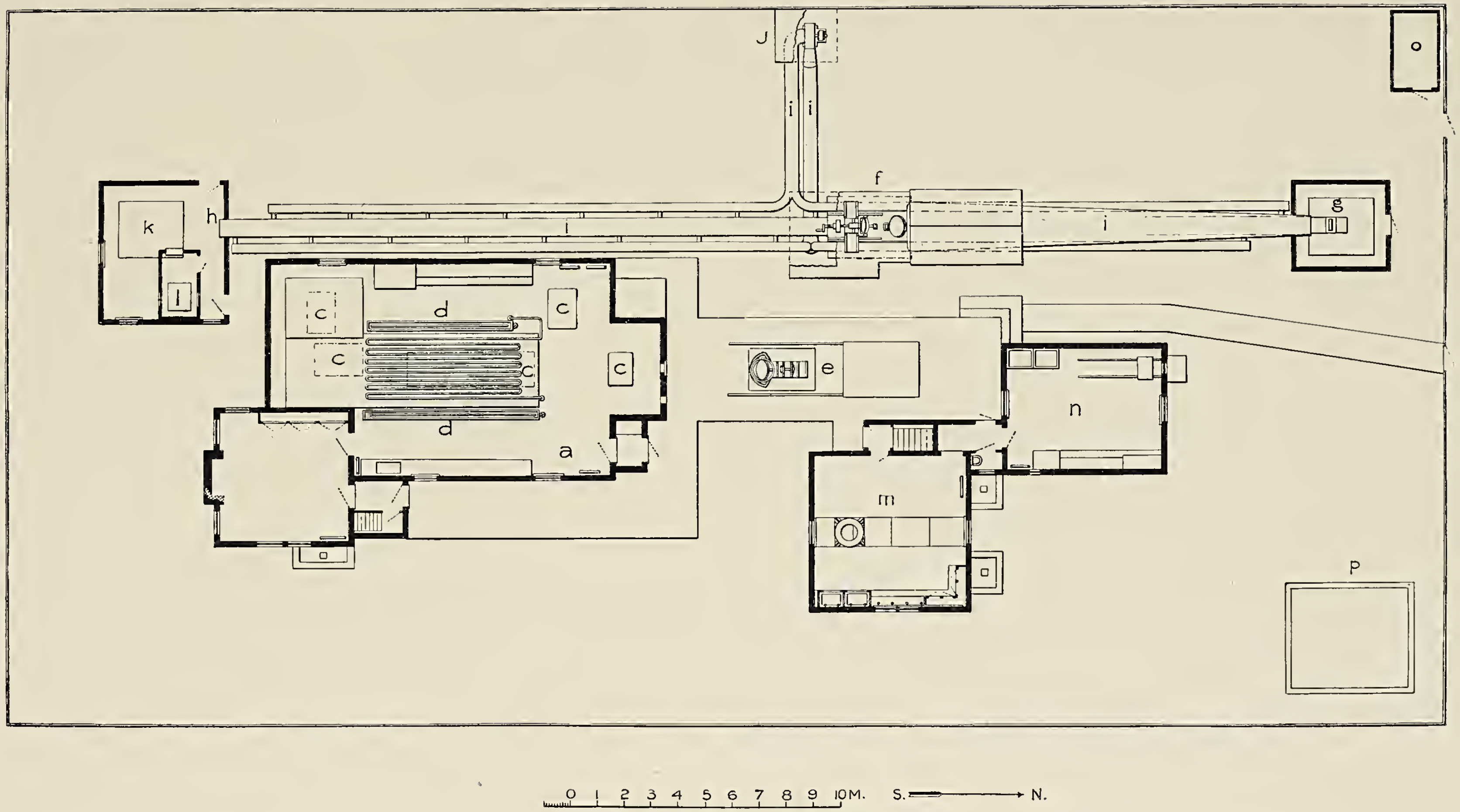
C. E. Mendenhall.
P. A. Draper.
N. E. Gilbert.
J. R. Benton.
S. A. Mitchell.
L. R. Ingersoll.

By request of the Chief of the Weather Bureau, Mr. H. H. Kimball, of the Weather Bureau, was assigned to the Observatory for instruction in spectrobolometric work for five months beginning May, 1905, during which time his services were freely at the disposal of the Observatory for work promoting such instruction.

Miss F. A. Graves was appointed computer on January 10, 1906. Miss C. V. Barber served under temporary appointment as computer from January 2 to June 25, 1907. Miss M. L. Scott served under temporary appointment as computer from July 5 to August 10, 1907. Mr. Kramer has continued instrument maker to the Observatory, and Mr. J. C. Dwyer has assisted in the computations since April 1, 1905.

Buildings and inclosure.—In order to make room for the equipment used in the research on solar transmission, the photographic dark room was removed in 1902 to a position north of the laboratory erected in 1898, and these two buildings are now connected by a covered passageway. In 1904 three shelters were erected to cover, respectively, the cœlostat, concave mirror, and spectrobolometric apparatus used for the research just mentioned. To accommodate these improvements the Observatory inclosure has been enlarged on all sides, and now includes 15,575 square feet. The present arrangement of the buildings and inclosures is shown in Plates I and II.

Referring to Plate II, P is a fireproof shelter for electrical purposes; J, F, G, and K are shelters for the long-focus horizontal telescope and its appliances; O is a portable shelter now used as a storehouse, but used for photographic purposes in the eclipse expedition of 1900; N is the photographic dark room; M is a laboratory and computing building of two stories; A is the main laboratory room, which contains the spectrobolometric apparatus and the office and library; E is the siderostat shelter.



PLAN OF THE OBSERVATORY INCLOSURE.

PART I.

DETERMINATION OF THE INTENSITY OF THE SOLAR RADIATION OUTSIDE THE EARTH'S ATMOSPHERE, OTHERWISE TERMED "THE SOLAR CONSTANT OF RADIATION."

Chapter I.

METHODS OF DETERMINING THE "SOLAR CONSTANT" OF RADIATION.

"If the observation of the amount of heat the sun sends the earth is among the most important and difficult in astronomical physics, it may also be termed the fundamental problem of meteorology, nearly all whose phenomena would become predictable, if we knew both the original quantity and kind of this heat; how it affects the constituents of the atmosphere on its passage earthward; how much of it reaches the soil; how, through the aid of the atmosphere, it maintains the surface temperature of this planet; and how, in diminished quantity and altered kind, it is finally returned to outer space." [1]

The importance of the determination of the intensity of solar radiation is even more enhanced if we admit the possibility that the amount which the sun sends the earth is not constant, but varies notably. To provide sound means of estimating the intensity of the sun's radiation at all times and to determine the question of its variability are the principal objects of the present investigation.

ATMOSPHERIC TRANSMISSION.

Owing to the frequent and often great changes in the transparency of the earth's atmosphere, caused by differences in humidity, haze, and dust, long continued series of observations of the intensity of the solar radiation at the surface of the earth can not furnish certain evidence of variability of the sun, unless supplemented by trustworthy estimates of the loss of intensity of the solar beam during its passage through the atmosphere. The earliest investigators of this subject assumed that the atmosphere could be treated as a medium of uniform transparency, so that in the passage of the beam through successive thin layers of the atmosphere, each of which produces equal barometric pressure, a constant fraction of the incident light is transmitted by each layer, so that if the intensity were originally A, then it becomes Ap, Ap^2, Ap^3, . . . Ap^n, after passing layers 1, 2, 3, ... n, each of which transmits a fraction p.

[1] Langley, Report of the Mount Whitney Expedition. Professional Papers of the Signal Service, XV, p. 11.

This leads to the exponential formula of Bouguer and Lambert, used by Herschel and Pouillet in their celebrated researches on the intensity of solar heat, and which may be expressed as follows, where E_0 is the intensity of the beam outside the atmosphere, E its intensity at the surface of the earth, a the fraction of the incident beam transmitted vertically through the atmosphere at normal barometric pressure B_0, m the ratio of the mass of air traversed to that which would be traversed at vertical incidence, and B the barometric pressure prevailing at the time:

$$E = E_0\, a^{\frac{B}{B_0}m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

It was shown by Forbes and others, and with especial clearness by Langley in his researches on Mount Whitney and at Lone Pine, in 1881, that one assumption made in obtaining this formula, namely—that successive thin layers of air, each producing the same increment of barometric pressure, transmit the same fraction of the incident light—is entirely false; and that in fact the air layers become less and less transparent toward the earth's surface. But Langley showed also that the exponential formula would still approximately apply if, instead of making the assumption just stated, we assume that the atmosphere is composed of thin layers concentric with the earth, each one of uniform transparency, but each differing slightly from the next adjacent one in transparency. This may be proved as follows:

PROOF OF FORMULA FOR TRANSMISSION.

Imagine the atmosphere to be made up of n concentric layers so chosen in thickness as to produce separately equal barometric pressures, and let the number n be so great that the transparency of any single layer is sensibly uniform, although the layers may differ from each other in transparency by any gradual progression. The index of refraction of air is so near unity that there will be no sensible regular reflection in passing from one layer to the next, and the transmission of each layer may be expressed exponentially by Bouguer's formula, but with different coefficients of transmission for the several layers.

Thus, suppose E_0 to be the original intensity of a beam of light incident upon the outermost layer at the angle whose secant is m.

Then after passing successive layers the remaining intensities become—

$$E_1 = E_0 a_1^{m_1}, \qquad E_2 = E_0 a_1^{m_1} a_2^{m_2}, \qquad E_n = E_0 a_1^{m_1} a_2^{m_2} \ldots\ldots a_n^{m_n}$$

The value of the secant of the angle of incidence will change slightly in passing from layer to layer from two causes: First, the curvature of the earth; second, the refraction of the beam in air. These causes produce opposite effects, the first tending to increase the angle of incidence, the second tending to diminish it as the beam approaches the earth's surface. Their combined effect is dependent on the height to which the atmosphere exercises absorption and on the distribution of density with the height. But it is generally supposed that the absorption of the air above 40 miles from the earth's surface is negligible, and, remembering that the atmospheric density diminishes with the height, it appears that for zenith distances less than 70° the effect of change of the secant of the angle of the incident beam from the outermost to the innermost layer of the atmosphere will not introduce error greater than 1 per cent.[1] Accordingly for zenith distances less than 70° we may write approximately

$$E_n = E_o \, (a_1 a_2 \, . \, . \, . \, . \, . \, a_n)^m \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \quad (2)$$

The symbols a_1, a_2, ... a_n denote constants (providing no change of transparency occurs during the interval of time in question), and their values are each slightly less than unity. We may substitute for their product a single constant a, itself a proper fraction, and remembering that E_n is the intensity at the earth's surface, above denoted simply by E, we have

$$E = E_o a^m \, . \quad (3)$$

LIMITATIONS OF FORMULA.

No mention is made in this expression of the barometric pressure, but it is easy to see that an alteration of barometric pressure would signify, under the conventions adopted in deriving the formula, a change in the number of layers n. This would cause an alteration of the quantity a, which is the continued product of the transmission coefficients of the layers, by introducing additional multipliers a_{n+1}, a_{n+2}, ..., or by the withdrawal of some a_{n-1}, a_{n-2}, . . . Since we have no means of determining the value of the terms so introduced or taken away, there is no means of correcting for change of barometer in the use of the expression (3), and it would, for instance, be impossible to compute, from knowledge of the values of E, E_o, a, and m for one station, what would be the value of E at some station of different barometric pressure. But as we know that in general the lower layers of the air have smaller transmission coefficients than the upper ones, owing to the generally low level of the larger quantities of dust and humidity, it may be shown that the use of formula (1) with its factors for barometric pressure would yield too small values if we should use data obtained by observation at a low station to compute the radiation reaching a higher one.

We conclude, then, that if within a cone of 70° zenith distance the earth's atmosphere may be regarded as composed of concentric layers, each of uniform transmission within the range of zenith distances contemplated, but each differing by any gradual progression in transparency from its neighbors, and if within each separate layer equal masses of air taken in succession transmit equal fractions of the incident light, then the intensity of the light at the earth's surface may be expressed

[1] This matter will be further discussed on a subsequent page.

as a simple function of the apparent zenith distance of the luminary; and the intensity of the light outside the atmosphere may be computed if we know its intensity at the earth's surface for different zenith distances. This information does not enable us, however, to compute the intensity at any other station within the outer limit of the atmosphere, so that our formula is strictly for purposes of extrapolation to the outer limit of the atmosphere, and not at all for interpolation within the atmosphere.

In order to determine readily the constants of expression (3) it is convenient to take logarithms of both members.

Thus

$$\log E = m \log a + \log E_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Regarding E_0 and a as constant during the observations, the expression (4) takes the form of the equation of the straight line. Hence if observed values of log E be plotted as ordinates and corresponding values of m as abscissæ, the constant (log a) is the tangent of the inclination of the resulting straight line and E_0 is the intercept on the axis of ordinates.

FORMULA APPLICABLE ONLY TO HOMOGENEOUS RAYS.

Unfortunately, there is still another limitation to the field of application of this formula, for, quite apart from the non-uniform transparency of the different layers of the air, each single layer is of different transparency to rays of different wave-length, and, as shown by Langley in 1881, it is a necessary consequence of this that successive equal thicknesses in the same layer transmit constantly increasing fractions of the incident compound beam; and the transmission coefficient determined in the manner just described, from high and low sun actinometer observations of the total solar radiation, is always too large. To repeat in substance his argument:

Suppose a ray composed of amounts A_0 and B_0 of light of two different wave-lengths to pass through a homogeneous stratum of air, and let a and b denote the fractions of the respective kinds of light transmitted by the stratum at vertical incidence. Suppose the intensity of the beam after transmission to be observed, first when the secant of the angle of incidence is m, and again when the secant is 2 m. Let C_1 and C_2 represent the results of these observations; let c be the coefficient of vertical transmission which they yield and C_0 the intensity of the beam before transmission, as computed from the observed data.

By Bouguer's formula:

$$C_1 = C_0 c^m \text{ and } C_2 = C_0 c^{2m}$$

$$\text{Hence } c^m = \frac{C_2}{C_1} \text{ and } C_0 = \frac{C_1^2}{C_2}$$

But the original intensity of the beam was in reality A_o+B_o; its intensity observed as $C_1=A_oa^m+B_ob^m$ and its intensity observed as $C_2=A_oa^{2m}+B_ob^{2m}$. If there is a difference between the real and computed intensity prior to transmission, this is $A_o+B_o-C_o$, and substituting for C_o we have the defect of C_o as follows:

$$A_o+B_o-C_o=A_o+B_o-\frac{(A_oa^m+B_ob^m)^2}{A_oa^{2m}+B_ob^{2m}}$$

$$=\frac{A_oB_o}{A_oa^{2m}+B_ob^{2m}}(a^m-b^m)^2.$$

This expression is always real and positive except when $a=b$, or when A_o or B_o vanishes, when it reduces to zero. The demonstration can readily be extended to treat a beam of greater complexity, and with similar results. Hence it follows that the application of Bouguer's formula to observations of composite radiation whose parts have been unequally transmitted must always lead to values of the original intensity below the truth.

From this we conclude that formula (3) can hold only when dealing with homogeneous rays. As the beam of the sun is far from being homogeneous, and as the transmission coefficients of its several parts differ greatly, it is now apparent that no just estimate of the intensity of the solar beam outside our atmosphere can be reached by the method of high and low sun observations without first treating the different wave-lengths separately.

APPROXIMATE METHOD FOR DETERMINATION OF "SOLAR CONSTANT."

It has been shown by F. E. Fowle[1] that notwithstanding the incorrectness of applying formula (3) to measurements of the intensity of the total solar radiation, still, when such observations are plotted logarithmically in accordance with equation (4), the resulting points lie nearly upon a straight line. The plotted observations depart from the best straight line in such a way as to render the curve slightly convex toward the origin, but the convexity diminishes as the air mass increases. The inclination of the best straight line is therefore continually decreasing, though at a decreasing rate, as we draw it to represent observations taken with greater and greater air masses, and thus the value obtained by producing such a line till it reaches zero air mass will fall more below the truth the greater the air mass from which it is extrapolated. Mr. Fowle computed the departures of such extrapolated values from the "solar-constant" values obtained by reducing spectrobolometric observations of the same dates by the most approved methods, and he found that the departures were surprisingly uniform in their magnitude for different days, providing that the extrapolations were always made from between definite air masses, although the transparency of the sky and the humidity of the air were very

[1] Smithsonian Miscellaneous Collections (quarterly issue), vol. 47, 4, 399, 1905.

different on the different days. As a result of many comparisons of this kind he found that the "solar constant" as computed from spectrobolometric work at Washington would in general be approximately obtained also from the pyrheliometric work alone, as follows:

Plot logarithms of pyrheliometer readings against air masses; produce the straight line best representative of these values between air masses 1.2 and 3.0 till it intersects the line of zero air mass; read off the logarithm corresponding to this intersection at air mass zero, and add 14 per cent[1] to the number corresponding.[2] Values derived by this empirical process seldom differ by 2 per cent from those derived by the aid of spectrobolometric work as described below, but naturally less confidence is placed in this abridged procedure than in the approved method now to be described.

PREFERRED METHOD FOR DETERMINATION OF "SOLAR CONSTANT."

To determine the solar radiation outside the atmosphere by the method of high and low sun observations of homogeneous rays it is necessary to separate the beam into its spectrum and to determine the intensity of the different rays of the spectrum for different zenith distances of the sun. Treating these observations by the process described under equation (4), coefficients of transmission are to be obtained for each ray. By the aid of these coefficients the intensity of each ray outside the atmosphere may be found, and by a summation of the intensities outside the atmosphere, divided by a summation of the intensities at the earth's surface, a ratio is obtained indicating approximately the relative total intensity of the beam outside and inside the earth's atmosphere. Simultaneously observations must be made by the pyrheliometer of the total intensity of the beam at the earth's surface in absolute units; for instruments like the spectrobolometer give only relative intensities, and there are besides many sources of inaccuracy attending the introduction of the optical parts of the spectroscope which would affect the result even if absolute measures could be made with the bolometer. The pyrheliometer reading for the given time, multiplied by the ratio obtained substantially as described above (but with modifications to be immediately mentioned), yields the value of the solar radiation outside the atmosphere.

Spectrobolometric observations extending from 0.37 μ to 2.5 μ appear to be sufficient to cover all regions of the solar spectrum where relatively appreciable radiation would be found outside the atmosphere, and the corrections to be introduced in allowing for the ultra-violet and infra-red beyond these limits are of the order of 1 per cent, as will be shown later. Carbonic acid gas absorption bands lie all beyond 2.5 μ, so that they need not be considered here.

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[1] See, however, Part I, Chap. VI, section 9.

[2] This correcting factor holds, approximately, it is repeated, at Washington, but not on Mount Wilson. At the latter station the correcting factor is smaller and more variable in amount.

SPECIAL TREATMENT OF WATER VAPOR ABSORPTION BANDS.

The existence of the great bands of water vapor absorption and of the smaller bands of selective absorption by other atmospheric gases between 0.37 μ and 2.5 μ complicates the method of procedure but little. For it is to be supposed that outside the atmosphere all these bands would disappear, so that we are justified in smoothing the curve over the top of such bands after extrapolating to the limit of the atmosphere. It is, of course, conceivable that what is loosely termed the general absorption of the atmosphere, namely, that which causes the gradually changing transmissibility for the successive rays of the spectrum, may in reality comprise excessively narrow and closely packed lines of selective absorption whose existence has never been separately demonstrated. If this is the case the spectrobolometric method would fail to discriminate the different transmission coefficients applicable to these supposed contiguous lines of great and small absorption, and consequently the "solar-constant" values obtained by the method now being discussed would be too small. Lord Rayleigh has, however, shown from general theory that the scattering of light by the molecules of gas composing the air is nearly or quite sufficient to account for its blueness and apparent absorption, and that this scattering is a continuous function of the wave-length, so that the hypothetical objection just mentioned has little weight.

The errors, uncertainties, and limitations of the method just described for determining the "solar constant" by high and low sun observations of homogeneous rays will be further discussed in Chapter III.

OTHER METHODS.

Another method of determination of the "solar constant" consists in observing simultaneously with the pyrheliometer at many stations distributed from the bottom to the top of a very high mountain. The observed values would, of course, increase from the lowest station to the highest. By plotting them in connection with the corresponding barometric pressures, a curve could be drawn which might be extrapolated to the barometric pressure zero, where the corresponding radiation value would be the result sought. This method requires many observers, and they would be subject to great discomfort at the high altitudes, unless some purely automatic recording apparatus could be employed successfully. The method has never been thoroughly tried. It would be greatly improved if correct automatic recording apparatus for the purpose could be carried by free balloons to enormous heights. Then we might expect the uncertainties of "solar-constant" determinations to disappear, but for the present this is impracticable.

EMPLOYMENT OF PREFERRED METHOD AT SEVERAL STATIONS.

The most satisfactory procedure for determining the "solar constant" now available, and the one here adopted and used, consists in making high and low sun observations with the spectrobolometer and pyrheliometer at several stations simultaneously—some at high, the others at low, altitude. All the observations are independently reduced by the processes already described, and the evidence of the accuracy of the results rests chiefly in the substantial agreement of the values obtained. The stations which have been employed in the present research are Washington, D. C., and Mount Wilson, California, separated by 3,000 miles in distance and by 6,000 feet in elevation. At the surface of the earth the pyrheliometer readings are generally from 25 to 50 per cent lower in Washington than on Mount Wilson. Reduced to the limit of the atmosphere, the "solar-constant" values agree closely with each other on the best days. The differences are generally within the limits of error reasonably to be anticipated as a consequence of the alteration of the transparency of the sky during the period required for the sun to pass from a high to a low altitude above the horizon.

Chapter II.

APPARATUS FOR "SOLAR-CONSTANT" DETERMINATIONS.

As stated in Chapter I, the method we have employed for determining the intensity of the solar radiation outside the earth's atmosphere is that devised by Langley about 1881, and termed the method of high and low sun observation on homogeneous rays. Two kinds of observing instruments are required: First, those adapted to measure relatively the change of intensity of each spectral ray as the path of the beam in the atmosphere alters; second, those adapted to standardize the readings of the apparatus used in the first part of the work. In the practice of the Smithsonian Observatory the atmospheric transmission of the different spectral rays has been determined by producing bolographs, the automatic records of bolometric indications, of the distribution of intensities in the solar spectrum of a 60° glass prism. These bolographs cover the region of spectrum from 0.37μ to 2.5μ in 11 minutes and are taken at frequent intervals throughout a forenoon or afternoon of observation. The standardization of the bolometric work has been done by making readings of the total intensity of the solar beam with the pyrheliometer, or actinometer, simultaneously with the spectrobolometric observations. It will be convenient to describe the apparatus employed in the two branches of the work under the two captions: A. Spectrobolometric Apparatus; B. Pyrheliometric Apparatus.

A. SPECTROBOLOMETRIC APPARATUS.

It is inconvenient to point the spectrobolometer directly at the sun; hence some instrument is required adapted to furnish a fixed horizontal beam of sunlight. In all the "solar-constant" work at Washington this purpose has been served by the Grubb single-mirror siderostat of the Foucault type, described and illustrated on pages 45 and 46 of Volume I of these Annals.

CŒLOSTAT.

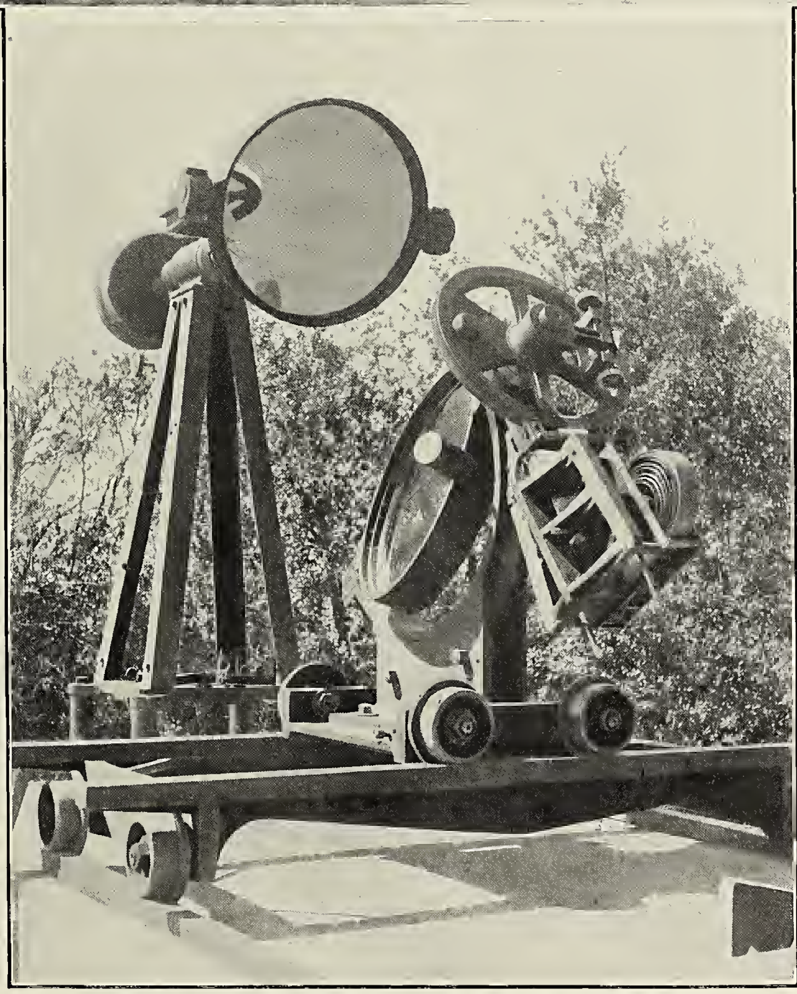
There was employed in the work on Mount Wilson a two-mirror cœlostat devised at the Observatory and constructed principally by Kahler of Washington and in part by A. Kramer, the Observatory instrument maker. The principle of the cœlostat was discovered by August about 1830, and consists simply in providing a mirror upon an axis parallel to that of the earth, with clockwork adapted to rotate the mirror at half the angular speed of the earth. As employed in this simple form by V. Littrow, Langley, and others (several of whom rediscovered the principle of the instrument independently) the beam is reflected in a horizontal direction whose azimuth depends jointly on the declination of the source of light and the latitude of the observing station. For solar work it would be necessary to alter the axis of observation through upward of 50° during a year at Washington, if the cœlostat were used in this simple form; and the mirror if adjusted to send the beam east would give a reflected beam of less and less cross section as the sun approached the west. To avoid these inconveniences, a second mirror was introduced at the Smithsonian Observatory in January, 1903, and this second mirror is placed nearly south of the first and at such a height as to intercept a beam reflected south and upward by the first mirror.[1]

To avoid shading the first mirror when the source of light is south of the celestial equator, and near the plane of the meridian, it is necessary at such times to move one of the two mirrors to the west or east, at the same time making the necessary readjustments to keep the beam reflected from the second mirror to the desired point. In cases where it is inconvenient to admit of any change whatever in the position and direction of the beam reflected from the second mirror, as in spectrobolometric work, it is necessary to move the first, or rotating mirror, east or west at the times when it would otherwise be shaded, then merely changing the inclination and not the position of the second mirror. The general course of the beam is shown in the diagram (Pl. VI).

When reflecting in the plane of the meridian the rotating mirror causes the reflected beam to rise at an angle with the horizontal equal to $90° - \varphi - \delta$, where δ and φ signify the declination of the source of light, and the latitude of the place of observation, respectively. Hence if h is the vertical distance between the centers of the two mirrors, the second mirror must be placed at a distance h tan δ. $(\varphi + \delta)$ south of the first, in order to intercept the reflected beam in the plane of the meridian. For solar work δ varies between the limits $\pm 23\frac{1}{2}°$, so that means must be provided to move one of the mirrors north and south at different seasons of the year.

The cœlostat employed on Mount Wilson is shown in Plate III. A carriage is arranged to be movable north or south on suitable horizontal tracks, and upon this carriage a second carriage may be moved east and west. A stationary base of equal height with the top of the upper carriage is provided, so that either mirror, as preferred, may be given the longitudinal and transverse motions on the pier. However, for the present work, the rotating mirror preferably rests on the movable carriages as shown. Two plane mirrors, each of 15 inches diameter, are mounted

[1] This form of two-mirror cœlostat was immediately adopted by Prof. G. E. Hale and others.



Spectrobolometer Shelter and Cœlostat, Mount Wilson.

Fig. 1.

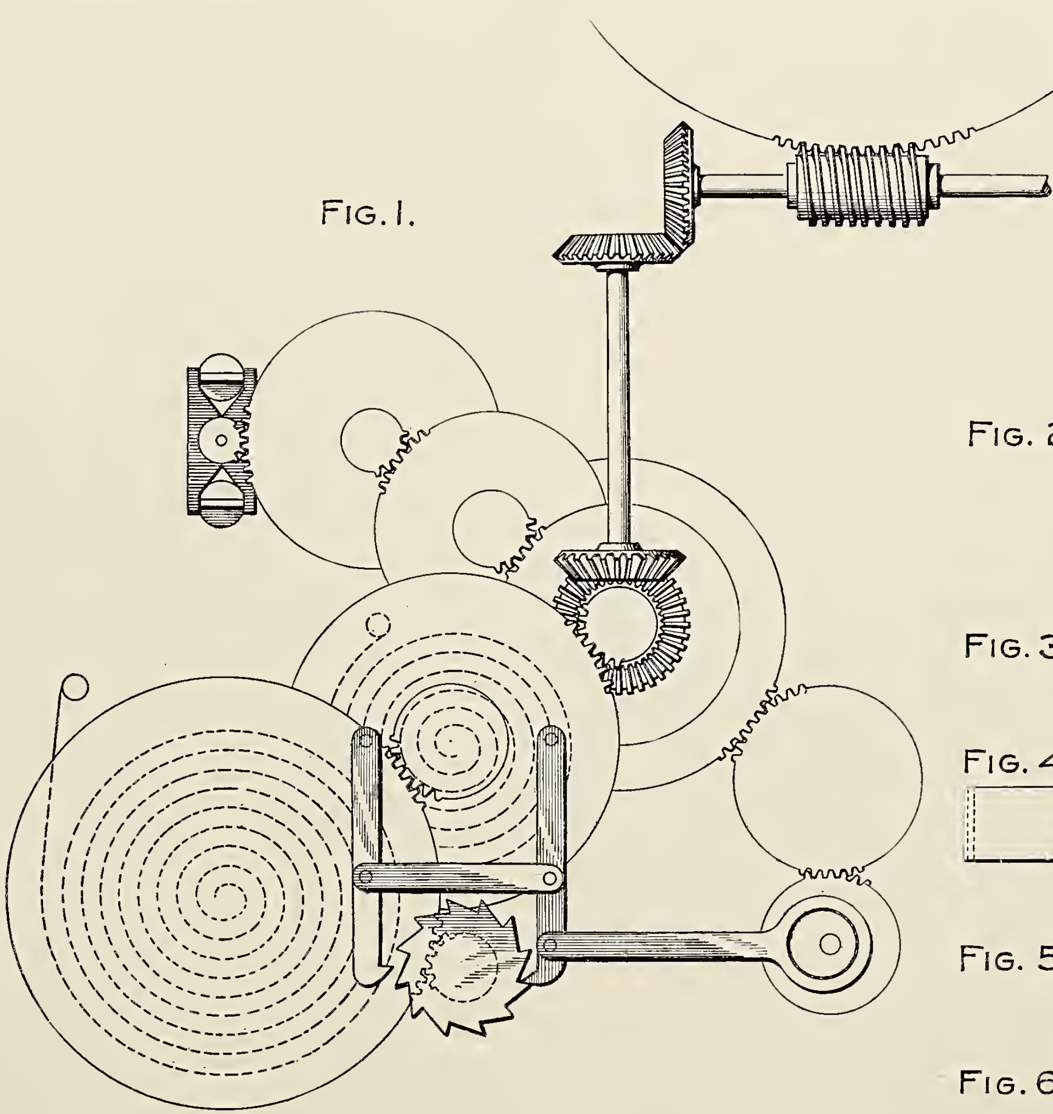


Fig. 2.

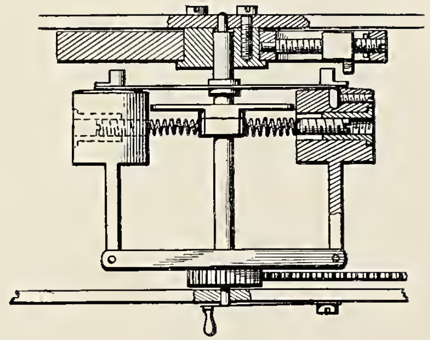


Fig. 3.

Fig. 4.

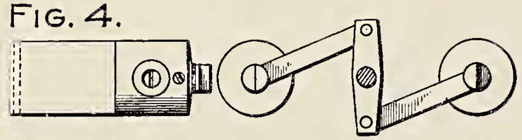
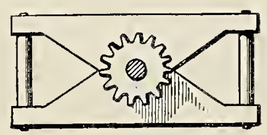


Fig. 5.

Fig. 6.



Cœlostat Driving Mechanism.

the one in a pan forming part of the polar axis of the instrument, the other on a steel tower of proper height. The second mirror pan, adapted for motion about two horizontal axes, has on its back a worm-wheel segment concentric with the axis passing through the trunnions of the pan, and this engages with a displaceable worm which is held against the worm-wheel segment by a spring, so that slow or quick adjustments of the mirror may be made according as the worm is engaging or not. The other horizontal axis of the second mirror and the polar axis which carries the first mirror are also provided with fine and coarse adjustments by tangent screws pressing on projecting pieces which may be clamped to the axes. The polar axis is driven by a 12-inch worm-wheel engaging with a worm, itself driven by a spring clock. This clock is modified from an inexpensive motor movement of the Seth Thomas Clock Company. As obtained from the makers it had merely a fly-vane governor, but this was replaced by a spring centrifugal governor of the form shown in the accompanying diagram (Pl. IV, figs. 2–6).

Certain advantages of a spring clock over a weight clock when, as in this case, the instrument must be moved to various positions, are sufficiently obvious, but there is the disadvantage arising from the non-uniformity of the tension of the spring. This is here overcome not by the well-known fusee and chain movement, as in old watch practice, but by introducing a secondary driving spring, itself wound to nearly constant tension by the primary springs. The secondary spring drives three trains of gearing, including, respectively, the cœlostat axis, the clock governor, and an escapement mechanism adapted to let the primary driving springs unwind at just the proper rate to keep the secondary spring wound to constant tension. These features are indicated by the accompanying diagram (Pl. IV, fig. 1).

This cœlostat is able to keep the direction of the beam constant within 1 minute of arc in half an hour, which is so close as hardly to require any hand adjusting for the purpose of bolographic work.

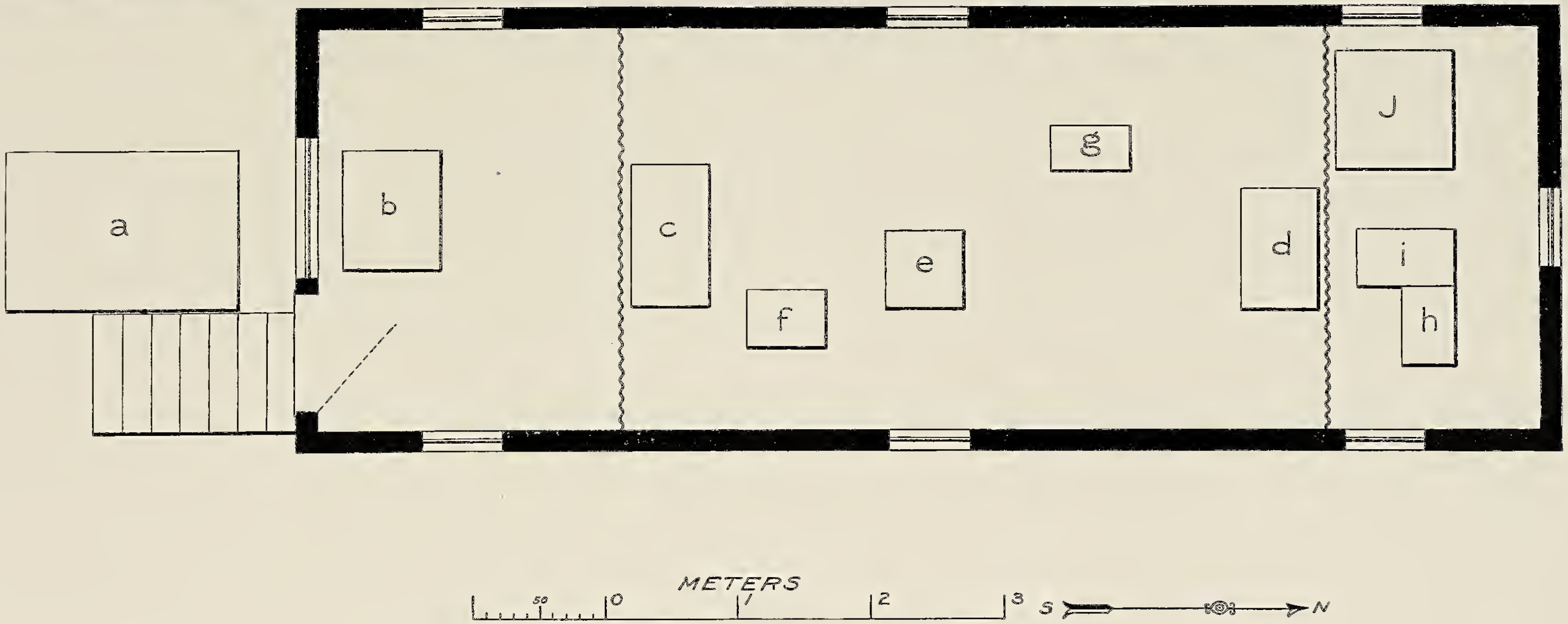
SPECTROBOLOMETRIC APPARATUS.

Plate V shows the ground plan of the shelter, including the disposition of piers, and Plate VI, figures 1, 2, gives the arrangement of spectrobolometric apparatus thereon as employed on Mount Wilson. Similar arrangements are in use at Washington, excepting as otherwise specified below. The following description refers to the Mount Wilson apparatus, but the differences of arrangement will be readily understood by reference to figures 3, 4, 5 of Plate VI, which illustrate the Washington apparatus. In Plate V, A is the cœlostat pier; B, pier for extra mirrors; *c*, pier for slits, secondary spectroscope, and image-forming mirror of main spectroscope; D, pier for collimating mirror of main spectroscope; E, pier for main spectroscope; F, pier for bolometer; G, pier for collimating mirror of secondary spectroscope; H, pier for driving-clock; I, pier for plate carrier; J, pier for galvanometer. In Plate VI, A and B are the plane cœlostat mirrors reflecting a beam northward in a horizontal direction from B[1] along the line B D. At C the beam passes through the vertical slit of the spectroscope and falls next upon the concave cylindric collimating mirror D, is reflected to the prism at E, thence passes to the plane mirror F for minimum deviation, and next is reflected by the spherical concave mirror G to focus at the bolometer H.

For the purpose of determining the reflecting power of the mirrors A, B, other similar plane mirrors are occasionally substituted for them, and again these latter are sometimes introduced at I, J, so that the beam then passes over the dotted course B J I before reaching the slit. If, for example, the observed intensity of a certain spectral ray is expressed by a when the usual mirrors A, B, are replaced by their substitutes I, J, and by b when all four mirrors A, B, J, I, are introduced to reflect the beam, then the fraction of the incident light reflected by the combination A, B, is $\frac{b}{a}$.

It is also necessary to know the relative amounts of different spectral rays transmitted by the spectroscope; for the form of the spectrum energy curve is much altered by the absorption of the mirrors and prism. Figure 2 is a diagram of the arrangement adopted for this purpose. The beam is reflected from B through a second spectroscope K, L, M, N, O, similar in form to the first, excepting that its collimator L is a spherical concave mirror instead of cylindric. This auxiliary spectroscope forms its spectrum upon the slit C of the main spectroscope, so that a narrow beam of nearly monochromatic light then passes through the latter, and its intensity can be observed at the bolometer by the usual automatic method described in Volume I of the Annals and to be described later in the present volume. Having thus obtained the intensity of such nearly monochromatic beams at numerous points in the spectrum, the bolometer is moved from the position H to the position H′, so that it occupies the usual position of the slit C, which is now taken away. By careful adjustments the same portions of the spectrum which before passed through the slit C now fall upon the bolometer at H′, and their intensities are read off by eye observations at the galvanometer scale. Suppose the intensities formerly observed at H to be represented by the quantities a, b, c, d, e, and those now observed at H′ for the same spectral rays to be a', b', c', d', e'; then the relative transmission of the spectroscope C, D, E, F, G, for these several spectral rays is in the relation of the quantities $\frac{a}{a'}, \frac{b}{b'}, \frac{c}{c'}, \frac{d}{d'}, \frac{e}{e'}$.

[1] In Washington the single mirror of the siderostat sends the beam southward horizontally, so that the whole spectroscope points in the opposite direction.



Ground Plan of Shelter for Spectrobolometric Work on Mount Wilson.

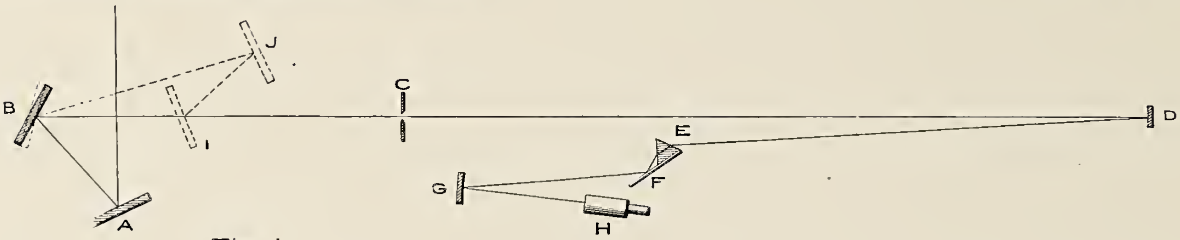


Fig. 1.

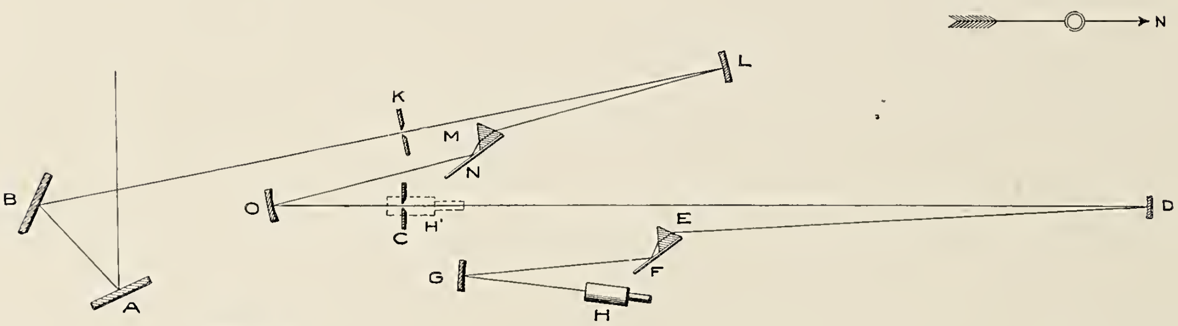


Fig. 2.

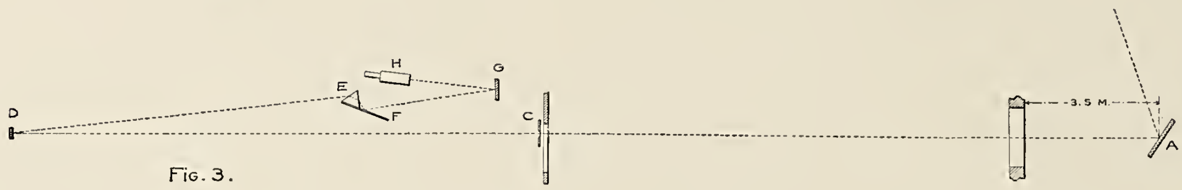


Fig. 3.

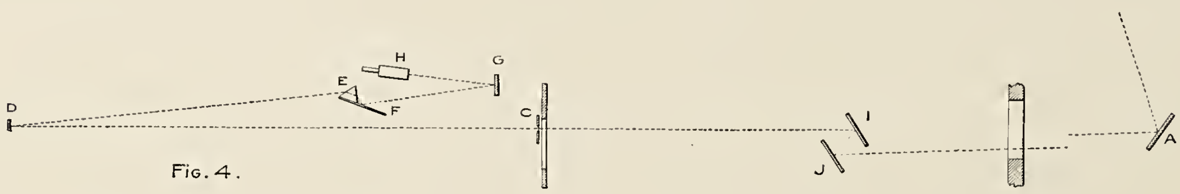


Fig. 4.

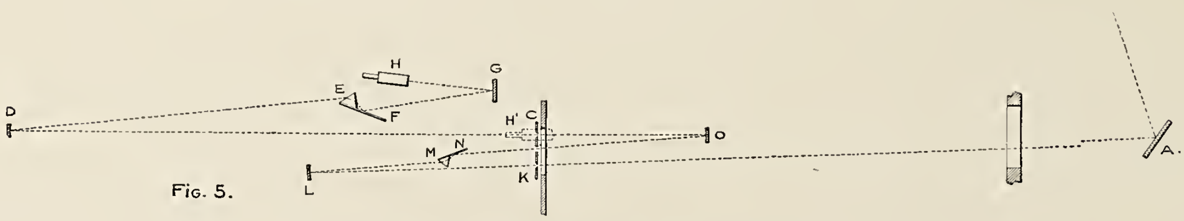


Fig. 5.

Diagrams of Spectrobolometer and Accessories.

SLITS.

The slits of the spectroscopes are each 10 cm. high and of variable width. For bolographs the width usually employed is about 0.5 mm., but for determining the relative absorption of the spectroscope wider slits must be employed, and that of the auxiliary spectroscope is generally as wide as 1.5 mm. for this work. The slits are all arranged to open symmetrically about a fixed center. One such slit constructed by Grunow and designed by Wadsworth is in use at Washington and is referred to in Volume I of these Annals. The other three are on the parallel ruler principle and were hastily made at the Observatory shop. Their design does not pretend to equal that referred to above for accuracy of setting, but they are easily constructed and satisfactory where wide slits of great range of width are required. When adjusting the auxiliary spectroscope for use in determining the relative absorption of the main spectroscope it is convenient to observe the spectrum with an eyepiece looking through the slit C. At such times it is advantageous to be able to throw the slit C open to a centimeter width rapidly, and the design used admits of this. Two grill diaphragms, having numerous horizontal apertures of different widths, are arranged to be placed in front of the main slit for the purpose of altering the effective height of it to reduce the energy at certain parts of the spectrum.

COLLIMATING MIRRORS.

The collimators of the auxiliary spectroscopes are concave mirrors of 230 and 350 cm. focus for the Washington and Mount Wilson outfits, respectively. Having been procured for other uses, their apertures are not specially adapted for the purpose, since an aperture of 15 cm. would be preferable in each case.

The collimators of the main spectroscopes for both outfits are concave cylindric mirrors each of about 5½ meters focus and placed with their straight elements vertical. Both are rectangular in aperture and are 18 cm. high and 12 cm. wide. Cylindric mirrors are preferred to spherical ones because the height of the spectrum in the focus of the object mirror is thereby rendered independent of the height of the slit, and dependent only on the focal length of the object mirror and the angular aperture of the sun. This makes it possible to use with advantage a slit as high as the height of the prism will admit without employing any cylindric lens to cut down the height of the spectrum before it reaches the bolometer. Both cylindric mirrors were furnished by Brashear, and when carefully adjusted with respect to the plane of the beam they appear to cooperate with the remainder of the spectroscope to promote excellent definition. One peculiar feature is always noted, however, when using them, namely, that the beams which they reflect are not of uniform brilliancy, so that if projected upon a white screen there is an appearance of alternate high-light and half-tone in vertical bands. This apparent defect is perhaps caused by the direction of stroke of the tool used in figuring, but it appears to introduce no appreciable error in the observations.

PRISMS.

The two large prisms[1] (by Brashear) used at Washington and Mount Wilson in the main spectroscope are both "ordinary telescope flint" glass, and are each of approximately 60° angle, and have faces 17 cm. high and 13 cm. wide. These prisms have almost equal dispersion, and the following table indicates approximately the positions of certain spectral lines. More exact measurements of their dispersion will be found in Chapter VI, Table 16, and the exact deviation for the A line, as given in these Annals, Volume I, is 46° 46′ 11″.0.

Designation.	K	F	D	A	ρ	ψ^1	ω_1
Deviation.....	51° 6′	48° 54′	47° 43′	46° 46′	46° 16′	45° 27′	44° 49′

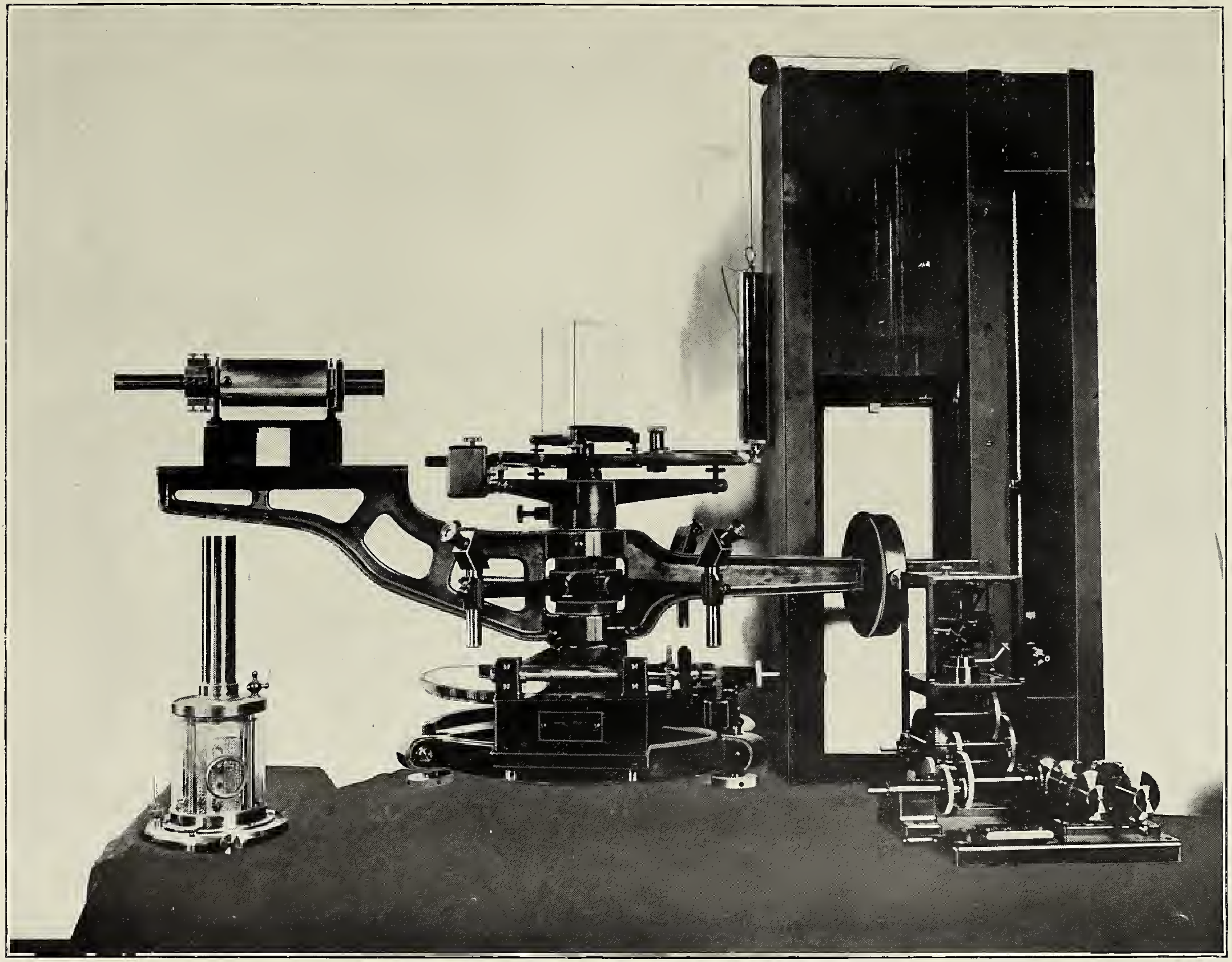
Two prisms (by Brashear) of approximately the same composition, dispersion, and angle, and with faces 8 cm. high and 8 cm. wide have recently been acquired for the auxiliary spectroscopes, and one of these was in use on Mount Wilson in 1906. At Washington a 60° prism with faces 5.8 cm. high and 5.5 cm. wide is still employed.

On Mount Wilson there was employed in 1905 a 60° prism loaned by Professor Hale and known by him as the "Pikes Peak prism," on account of his former use of it on Pikes Peak in company with Professor Keeler.

SPECTROMETER.

At Washington the large spectrometer (by Grunow) described and figured on pages 46 and 47 of Volume I of these Annals is employed in the main spectrobolometric outfit. A new instrument (by Warner & Swasey) of similar general form and dimensions, but modified in accord with the dictates of experience, was used on Mount Wilson. An illustration of this spectrometer and of a galvanometer, bolometer, clock, and plate carrier is given in Plate VII. The spectrometer has a divided circle 50 cm. in diameter, which turns about a vertical axis and which may be read by four fixed verniers to within 5″ of arc. The vernier microscopes are bent outward at an angle of 45° so that the observer reads from a convenient position in all cases. Upon the sleeve which carries the circle is clamped a segment of a worm-wheel for driving the circle by clockwork and a telescope support for carrying a telescope used to determine prismatic deviations and for other purposes. The prism table may be fixed to the vertical sleeve which carries the circle and observing telescope, or to the fixed vertical axis instead, so that the prism may

[1] One of these prisms was tested by the writer and Mr. W. S. Adams on Mount Wilson, and it was found that for visual observations near the *b* region of the solar spectrum it was possible to recognize as double, lines which are no more than 0.20 Ångström units apart.



Spectrometer by Warner and Swasey.

remain fixed while the telescope is used to observe prism angles and prismatic deviations, or the prism may turn with the circle, as in making bolographs, and in the method of measuring prism angles by a fixed telescope.

The whole prism table may be leveled by three screws, and it is further arranged to level the plate on which the prism stands independently, and to adjust the position of the prism laterally with respect to the axis of the spectrometer. A vertical axis on the prism table carries a rectangular plane mirror (F of Pl. VI, which is 17.5 cm. high and 25 cm. long), and means are provided by which this mirror may be set at any desired angle of azimuth with respect to the prism, or indeed the mirror and prism can be displaced wholly, and a grating substituted for the mirror. Two speeds of driving, one twenty times as rapid as the other, are provided by means of back gears on the shaft of the worm which engages with the worm-wheel mechanism above mentioned. A long shaft communicates motion to the worm from a clockwork, situated in the galvanometer room, which also drives simultaneously the photographic plate which records automatically the indications of the galvanometer, as will be described.

SPECTROMETER DRIVING-CLOCK.

An illustrated description of the clock in use at Washington is given in Volume I of these Annals, page 57. The one used on Mount Wilson (by Warner & Swasey) is similar, but there have been two alterations to adapt it to the present work. Referring to Volume I of these Annals, the shaft *n* projects in the opposite direction to that shown in Plate XIII, so that the plate carrier and galvanometer are on the same side of the shaft *m* as the spectrometer, which gives a more compact form to the building on Mount Wilson than would be possible with the old arrangement (see Pl. V, Vol. II). In the second place the bevel gear sleeve *e* has now two cones within it, which are themselves keyed to the shaft, so that these gears may be unclamped from their shaft by loosening the cones, and then the shaft *m* can be turned by means of a crank near the point *a*, so as to set the spectrometer at any desired position. A counter mechanism and divided circle indicates the number of half turns and one-hundred-twentieths of turns of the shaft *m*; so that when the back gears of the spectroscope are inserted in the train, the counter and divided circle record minutes and seconds of arc in the spectrum. For quick-speed bolographs, as produced in the present work, the back gears of the spectroscope are not used, and in such circumstances one half turn of the shaft *m* produces 20 minutes of arc displacement of the spectrum, so that differences of the readings of the clock counter are to be multiplied by 20 to reduce to differences of prismatic deviation. A similar modification of the clock to adapt it for setting the spectroscope from the clock room is in use in Washington, and the same speed ratios are employed.

The auxiliary spectrometers for carrying the prisms having the position M in figures 2 and 5, Plate VI, are both small instruments hastily devised and constructed for the purpose at the Observatory shop. They are provided with worm-wheel mechanisms and counters so that they may be set for any desired position in the spectrum.

BOLOMETER.

On Mount Wilson a form of bolometric apparatus was used in which all the adjuncts required to adjust its electrical balance are contained in a single small case operated mechanically from without. As the same devices are employed in Washington, but not in quite as highly improved a form, the description which follows will be confined to the Mount Wilson instrument.

The bolometer, invented by Langley in the year 1880, consists of a strip or strips of thin metal, blackened to absorb radiation, and so connected with an electrical circuit forming a Wheatstone bridge that the rise of temperature of the thin strip or strips, due to their absorption of radiation, causes a disturbance of the balance of the Wheatstone bridge, which in turn causes a flow of electricity through a sensitive galvanometer. In 1892, soon after the establishment of the Astrophysical Observatory at Washington, Langley introduced the great improvement of recording the indications of the galvanometer photographically on a sensitive film or plate moved by clockwork simultaneously with the motion of the spectrum over the bolometer, so that the investigation of energy spectra thus became largely automatic. The further improvements which have been introduced at the Astrophysical Observatory relate to the form of the case inclosing the bolometric apparatus, and to the methods of obtaining an electrical balance of the Wheatstone bridge, as well as to the improvement of the galvanometer. Many improvements were described in Volume I of these Annals, pages 47 to 56, but the new form of bolometer now to be described was devised at the Observatory in 1902 and 1903, and constructed in the Observatory instrument shop.

No change has been made in the part for absorbing radiation, which consists, as described in Volume I of these Annals, page 48, of a thin strip of platinum drawn and hammered to the desired dimensions while coated with silver, and blackened with camphor smoke after the silver has been dissolved with nitric acid, and the naked platinum strip carefully soldered upon its copper frame. For the work here described the bolometer strip is 12 mm. long and 0.06 mm. wide, and its thickness may best be estimated from the fact that its electrical resistance is about 4 ohms. For the sake of symmetry of conditions a second strip of platinum as nearly as possible like the absorbing strip in all respects, and situated as near the absorbing strip as practicable, but shielded from the radiation by a diaphragm, forms the second resistance arm of the Wheatstone bridge. The third and fourth arms of the bridge consist of two coils of platinoid wire which are joined with the two bolometer strips, and with the other parts of the circuit, comprising a battery (B), a galvanometer (G), and several slide wires (f_1 f_2 f_3 f_4 f_5) for adjusting the bridge as shown by the diagram, Plate VIII, figure 9. In this diagram the two bolometer strips are represented by *a*, *b*, and the two coils by *c*, *d*. Certain small additional resistances forming continuations of the slide wire loops (f_1 f_2 f_3 f_4 f_5) are shown at e_1 e_2 e_3 e_4 e_5 and these are adapted to provide a gradation of nicety of adjustment between the five different slide wire loops. Thick contact pieces (g_1 g_2 g_3 g_4 g_5) form sliding shunts on the slide wire loops, so that the resistances used in the several loops may be changed thereby. A resistance *h* is introduced in the battery circuit to reduce the current of the battery to about 0.08 amperes. The potential of the battery and the resistances of the several parts are as follows:

Designation.	*a*.	*b*.	*c*.	*d*.	e_1.	e_2.	e_3.	e_4.	e_5.	$f_1=f_2 \ldots f_5$.	G.	B+*h*.	Battery potential.
Resistance (in ohms)...	4	4	7.88	9.55	0.06	0.6	0.6	2.7	49.2	0.3	1.6	20	2 volts.

It will be noticed that the effect of moving the slider upon any one except f_5 of the several looped slide wires depends greatly upon the positions of all the other sliders, and that the effect of a movement of the slider through a definite distance at the outer end of any one of the slide wire loops is less than if a movement of the same magnitude occurred at the inner end. All the slide wires were at first arranged alike in this respect, and these variations of sensitiveness in adjustment were introduced in order that simple and convenient mechanical arrangements could be employed, and in order that no contact between conductors leading from the Wheatstone bridge to the battery or galvanometer should be a sliding one, and hence of possibly indefinite resistance. It was found on Mount Wilson that it would be desirable to have the effect of one of the slide wires independent of the positions of the contact pieces on the others, and adapted to afford a convenient means of comparing the sensitiveness of the apparatus at different times. Accordingly the arrangement as described in what follows was proposed, which includes such modifications as shall make the effect of slide wire 5 nearly independent. Assuming the other four sliders to be in their central positions, the effect of moving one slider at a time through its extreme range is as follows:

Designation of slider.	g_1	g_2	g_3	g_4	g_5
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Effect on the resistance of third arm of bridge..........................	1.7	0.12	0.04	0.009	0.10

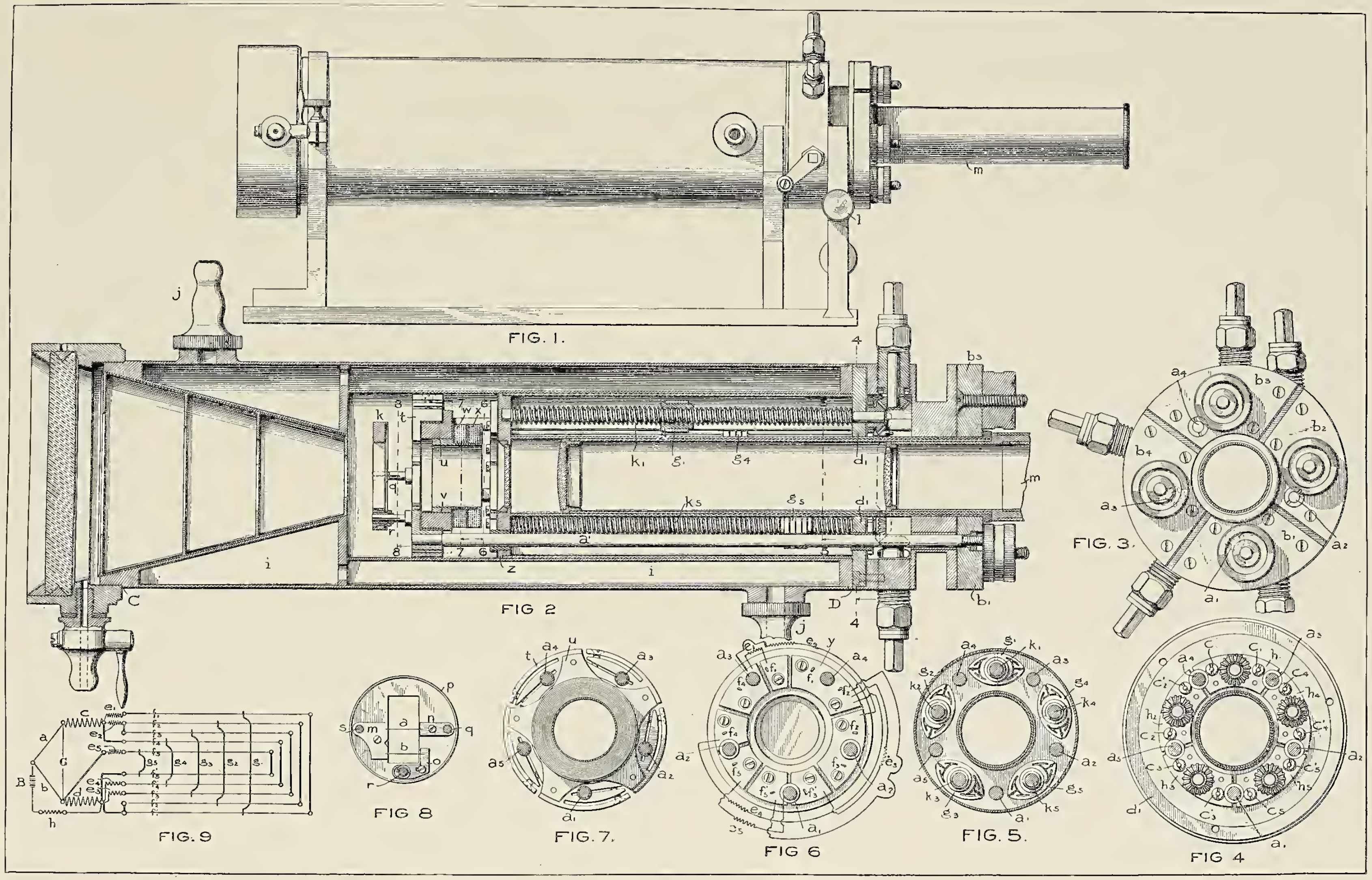
The fifth slide wire is intended solely for use to determine the sensitiveness of the apparatus and not for adjusting the balance.

These degrees of refinement of adjustment were chosen to meet any demands which it was thought could result from any increase of sensitiveness of apparatus which would ever occur. In ordinary practice thus far it is found that the use of the first and second slide wires is all that is required, and with the most sensitive bolometric arrangement ever used at the observatory the first four slide wires have been found abundantly sufficient for adjusting.

Turning now to the details of mechanical construction of the bolometric apparatus, as shown in Plate VIII, figure 1 gives a side elevation of the instrument complete, including all the parts necessary to bolometric work except a battery and galvanometer. Figure 2 shows a horizontal section; figure 3 an end view looking from the right. Figures 4, 5, 7, and 8 are sections looking from the right on the lines 4, 4, 5, 5, 7, 7, and 8, 8 of figure 2; figure 6, a section looking from the left on the line 6, 6 of figure 2. The instrument, as shown in section in figure 2, is separable at the points C and D into three parts having distinct functions. On the left of C is a cell in which a transparent plate or lens may be inserted and sealed by pouring wax in a groove around it. By means of the cock shown at the side of this cell the interior chamber containing the bolometer may be exhausted, if desired. As the reflection and absorption of light by a plate or lens are objectionable when measurements of the relative intensity of different spectral rays are in question, the use of such plates or lenses is avoided in the spectrobolometric determinations of the "solar constant," and the reader may consider the glass plate shown in figure 2 as dispensed with in "solar-constant" work.

The second part of the apparatus consists of the double-walled jacket *i i*. Nozzles *j j* are shown communicating with the space between the walls of this jacket, so that, if required, water or some other liquid may be introduced to keep the apparatus at a more constant temperature. Of late years it has not generally been found necessary for steadiness or freedom from drift to do this, and the use of a liquid in the jacket is now usually dispensed with. At the front of the bolometer case is shown a conical tube with diaphragms, through which the rays enter the bolometer chamber. The diaphragms are provided with apertures of such shape that rays may fall on the central strip of the bolometer (shown at *a* in fig. 8), while the side strip *b* is hidden. Different sets of diaphragms may be introduced to suit different angular dimensions of the converging beam.

We will now describe the electrical and mechanical working parts of the bolometric apparatus, contained in a detachable portion of the apparatus, which may be slipped in or out of the jacket, separating at the point D. The bolometer proper, shown in figure 8, and at *k*, figure 2, comprises the two camphor-smoked platinum strips *a*, *b*, soldered at their ends to the sheet copper pieces *m*, *n*, *o*, which themselves are attached by insulated screws to the mica-covered brass frame *p*. Copper tubes soldered to the copper pieces *m*, *n*, *o*, and insulated by fiber tubes from the frame *p*, admit the three posts *q*, *r*, *s*, whose function is to connect the bolometer strips electrically with other parts of the apparatus. These posts are



Bolometer and its Adjuncts.

split at the ends, and wedges are inserted in the split ends to insure perfect connection with the bolometer. The posts *q, r, s* are set in the copper piece *t* shown in figures 2 and 7, and this is divided, as shown, in five parts, all of which are fastened by insulated screws to the brass piece *u* (figs. 2 and 7), which is insulated from *t* by mica sheets. The piece *u*, besides rigidly holding the five sections of *t*, serves also to hold the bobbin *v*, on which are wound the two platinoid coils *w, x*, which correspond with *c, d* of figure 9. All the parts, *k, t*, and *u*, thus far spoken of, are supported on the ends of five copper rods ($a_1a_2a_3a_4a_5$) shown in section in figures 4, 5, 6, and 7, and some of which appear also in figures 2, 3. The rod a_5 does not extend entirely to the front of the instrument, but the other four join the four binding post pieces ($b_1b_2b_3b_4$, fig. 2), to which are attached the wires leading to the battery and galvanometer. The copper pieces *t* (figs. 2 and 7) have in each section a radial clamping screw which closes up two slots so as to pinch tightly not only the copper rods ($a_1a_2a_3a_4a_5$), but also the four wires leading from the coils *w, x*. Between this point and the front of the instrument all the rods just mentioned are insulated excepting a_3 and a_4, which are soldered to two of the eight sections of the copper piece *y*, shown in figure 6. This sectional piece *y* is fastened by insulated screws to a brass plate *z*, shown in figures 2, 6, from which it is insulated by mica sheets. To the several sections of the copper piece *y* are soldered the ten rear ends of the platinoid slide wires $f_1\,f_2\,f_3\,f_4\,f_5\,f'_1\,f'_2\,f'_3\,f'_4\,f'_5$ of figures 6 and 9. Besides these there are also soldered to the sections of the piece *y* the resistance wires $e_1\ e_2\ e_3\ e_4\ e_5$, figures 6 and 9. The slide wires pass through insulated holes in the piece *z*, thence through the contact blocks $g_1\ g_2\ g_3\ g_4\ g_5$ (figs. 2 and 5) and through insulated holes in the brass piece d_1 (figs. 2 and 4) and are drawn taut by nuts ($c_1\ c'_1$, etc.) pressing against the insulated copper pieces $h_1\ h_2\ h_3\ h_4\ h_5$ (fig. 4). The contact blocks $g_1\ g_2\ g_3\ g_4\ g_5$ are split both longitudinally and transversely so as to press with some elasticity against the slide wires at numerous points of contact. These blocks have central cores of "fiber" which are threaded within to admit the adjusting screws $k_1\ k_2\ k_3\ k_4\ k_5$ (figs. 2 and 5). These screws have their bearings in the pieces *z* and d_1, and are rotated by beveled gears communicating with crank shafts operated from the outside of the case, as shown in figures 1, 2, 3, 4. The whole interior apparatus can be rotated about the axis of the instrument by means of tangent screws, shown at *l* in figure 1; so that the bolometer strip, as observed through the eyepiece *m* (figs. 1, 2), can thus be made parallel to spectrum lines.

In the observations on Mount Wilson during the year 1905, a "drift" of from 2 to 10 cm. was frequently experienced in the forenoon observations, accompanied by a slight change of the sensitiveness of the bolometric apparatus, or of the galvanometer itself, it was uncertain which. Both of these effects attended the rise of temperature of the observing shelter and were thought to be caused thereby. The "drift" was almost wholly eliminated from the Mount Wilson observations of 1906 by substituting for a small part of one of the platinoid resistance coils (which, with the bolometer threads, form the Wheatstone bridge) a short piece of copper wire. A similar device for eliminating the effects of temperature changes of resistance coils was patented by Callender in 1888, but had till now been overlooked by us as a very simple and certain method of overcoming "drift" in a bolometer.

The change of sensitiveness noted may have been due not only to changes of the temperature of the bolometric apparatus and galvanometer, but also to the diurnal variation of the earth's magnetic field. So far as it is due to the local rise of temperature, its effect was reduced in 1906 by thickening the walls of the bolometric shelter and screening it from the sun, and by protecting the galvanometer and bolometer themselves more effectually from the variations of temperature about them. It will be shown on a later page how the change of sensitiveness of the bolometric apparatus is determined and allowed for in the reduction of the observations.

BATTERY.

A storage battery is found to give best results upon the bolometer circuit. At Washington there is used a battery (by the Electric Storage Battery Company, of Philadelphia), of five cells of Type D 5 in parallel, but on Mount Wilson a battery (by the same company) of two cells of this type in series gave apparently as good results.

GALVANOMETER.

For the purpose of producing quick-speed bolographs of the solar spectrum, a galvanometer of great sensitiveness, small resistance, and short time of swing is required, and it is necessary that it shall be very little affected by ground tremors and by fluctuations of the magnetic field. As these requisites are somewhat contradictory, a balance of desirable and undesirable elements must be struck to give the best general result. In the Astrophysical Journal, Volume XVIII, page 1, 1903, there appeared an article by C. G. Abbot upon galvanometer construction, which embodies most of the considerations leading to the design of the galvanometers in use for spectrobolometric purposes, and it will be sufficient here to state only the final forms adopted. As the instruments in use at Washington and Mount Wilson are alike excepting in the (here) unimportant feature of the design of the case, no distinction will be made between them in the following description. The galvanometers are of the reflecting type, modified from the design of Sir William Thomson (Lord Kelvin). To promote mechanical and magnetic steadiness the suspended system contains eight groups of six magnets each, arranged as shown in Plate IX, figure 1, so that the suspended system is both heavier and naturally more astatic than suspensions for a four-coil galvanometer of similar sensitiveness. The use of sixteen coils instead of four involves a deliberate sacrifice of about one-half in sensitiveness

Fig. 1.

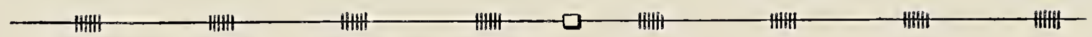


Fig. 2.

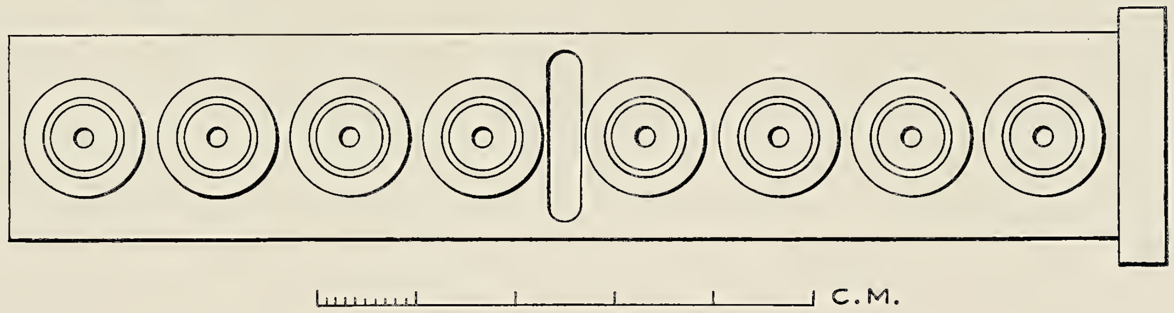
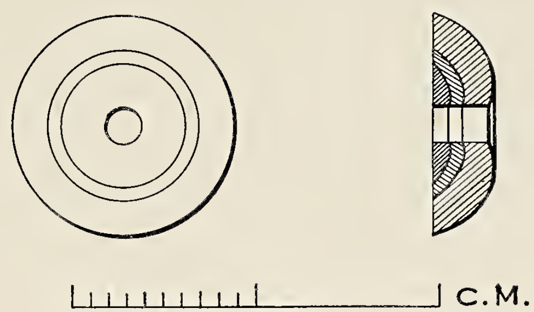


Fig. 3.



Galvanometer Needle and Coils.

as compared with a four-coil instrument of the same total resistance, but this is offset by the greater steadiness. A mirror 1.5 mm. high and 1 mm. wide, selected from numerous pieces of platinized microscope cover glass, is fixed to the glass stem of the suspension, and the whole system weighs about 10 milligrams. It is suspended by a quartz fiber about 20 cm. long and about 0.003 mm. in diameter.

Figure 3 of Plate IX shows the form of coils used. They are each of about 0.1 ohm total resistance, wound in three sections of the forms shown, with single white silk insulated copper wire Nos. 32, 26, and 24, B. and S. gage, respectively. The coils, arranged as shown in figure 2 of Plate IX, are connected in series and have a total resistance of about 1.6 ohms. Means are provided for raising or lowering and leveling the coil supports and for increasing or diminishing the horizontal distance between the two banks of coils.

It is customary in taking bolographs to employ atmospheric air pressure in the case and to regulate the time of swing by the aid of a magnet above and one below the galvanometer, so that a half vibration, or single swing, of the needle system occupies 1.5 seconds or thereabouts. Under the circumstances just detailed a deflection of 1 mm. on a scale at 1 meter is produced by a current of about 5×10^{-9} amperes.[1]

In Washington the galvanometer is mounted on the Julius suspension described in Volume I of these Annals. On Mount Wilson the ground tremors are so much less than in Washington that it was found satisfactory to use merely a pile of stone blocks each 12 inches square and 4 inches thick, separated at the corners by rubber blocks 1½ inches thick. Both at Washington and on Mount Wilson the foundation of the apparatus is a pier extending several feet below the surface of the ground. The degree of freedom from vibration usually experienced is shown by the records given in Plate XIII, from which it appears that accidental vibrations as great as 1 millimeter rarely occur, and that the average accidental vibrations are of an amplitude of about 0.3 mm. This includes everything which disturbs the bolographic records, such as variations of the battery current, gusts of air on the bolometer, etc., and not alone the mechanical and magnetic disturbances of the galvanometer itself.

PHOTOGRAPHIC PLATE CARRIER.

On Mount Wilson the same plate carrier described and illustrated on page 58 of Volume I of these Annals was used. A new plate carrier of similar construction (by the Warner & Swasey Company), but adapted to include plates 10 inches by 24 inches instead of 8 inches by 24 inches, is now in use at Washington.

[1] The galvanometer employed at Mount Wilson has been used in Washington with the air exhausted to 0.2 mm. pressure, at a time of single swing of 7 seconds, and with a scale distance of 4 meters. A current of 2×10^{-12} amperes could then be recognized certainly.

SPEED OF DRIVING.

As described in Volume I of these Annals, a clockwork moves the spectrum horizontally across the bolometer strip, and at the same time moves the photographic plate vertically in front of the galvanometer mirror, and thus is produced by the small spot of light reflected from the galvanometer mirror a sinuous photographic trace, whose rectangular coordinates indicate the intensity of radiation corresponding to prismatic deviations in the spectrum. It is important to produce these energy curves as rapidly as is consistent with the desired accuracy, for, especially at low sun, the rate of change of intensity for points in the visible spectrum is quite rapid, and furthermore, it is desirable to get a considerable number of observations at each wave-length. On the other hand, if the rate of driving be too rapid there is not time for the bolometer and galvanometer to respond properly to the changes of intensity in the spectrum, so that the form of the energy curve is thereby in error. As a compromise between these considerations the spectrum is caused to pass the bolometer at the rate of 40 minutes of arc in 1 minute of time, and the plate moves vertically at the rate of 4 cm. in a minute of time, so that on the plate 1 cm. in abscissæ corresponds to 10 minutes of arc in the spectrum.

B. PYRHELIOMETRIC APPARATUS.

In the "solar-constant" work the bolometer serves to measure relatively the intensities of the different spectral rays at the earth's surface, and the losses which these rays severally suffer in traversing the air; but it does not determine the total amount of radiation received in terms of an absolute, or even of an invariable, scale of energy. Its relative measurements must be standardized in some way before the results can be used to determine either the absolute magnitude or the possible changes of the solar radiation outside the atmosphere.

When the work was begun in Washington plans were made to compare the solar energy spectrum with the known energy spectrum of a perfect radiator ("absolutely black body") of known temperature on each day of observation. For this purpose a Kirchoff-Wien "black body," after the design of Lummer and Pringsheim, was procured[1] in 1902. This instrument comprises a tube of refractory material closed at one end and heated by a platinum tube outside of it, which carries an electric current. The emission is observed through the open end of the tube, and as this forms a chamber having walls of uniform temperature the radiation emitted includes approximately the full complement of rays of each wave-length proper to the temperature of the body, independently of the material of which the emitting substance is composed. If such a radiator were to be placed before the slit of the spectrobolometer, its radiation of each wave-length would suffer the same fractional

[1] Thanks are due the director of the Reichsanstalt and Messrs. Lummer and Pringsheim for their valuable assistance in this matter.

absorption in the spectrobolometer as rays of equal wave-lengths from the sun, and accordingly there would be no occasion to determine these fractions at all, for the true amount and spectral distribution of the radiation of the perfect radiator being known, then the true amount and spectral distribution of the sun's radiation would be found by multiplying each intensity in the true energy curve of the perfect radiator by the ratio between the heights at the corresponding wave-length in the observed energy curves of the sun and the perfect radiator. But the temperature safely attainable with this perfect radiator is not more than a third of the apparent temperature of the sun, and hence, in accordance with the laws of radiation, the rays of short wave-length from such a source would be of very much lower intensity as compared with the rays of long wave-length than is the case in the solar spectrum. Hence there would be for the shorter waves, which are most important in the solar spectrum, a relatively large error of comparison between the two energy spectra, and indeed it proved in practice impossible to obtain a sufficiently accurate comparison in this region of spectrum. Furthermore, the inconvenience, delay, and expense involved in using the perfect radiator in this manner is so considerable that it appeared undesirable to pursue the project further.

Abandoning, then, the idea of forming a comparison spectrum from a known source of radiation, it might nevertheless appear plausible to employ a Leslie cube or other source at a low temperature, easily managed, and to standardize the bolometer from time to time by noting the deflection due to the full radiation of such a body. It would be necessary in this case to measure accurately the loss of energy in the spectroscope, and also the aperture of the slit employed, and to take account of the effect of humidity of the air; otherwise no estimate of solar radiation could be made. The difficulty of such measurements is too great to warrant the expectation of sufficient accuracy, and this method must therefore be abandoned.

Other methods of standardization thus failing of sufficient accuracy, full reliance has been placed in the pyrheliometric method adopted by Langley at Allegheny and Mount Whitney. The bolographs exhibit the form of the energy spectrum of the sun rays after passing through the atmosphere and after being reflected and transmitted by the optical apparatus. Proper corrections are determined and applied so that the bolographic curve is altered in form to represent the distribution of the intensity for the different wave-lengths just as the sun ray reaches the surface of the earth and before it suffers loss in being transmitted by the optical apparatus. In this form the height of the curve at each point represents the intensity of radiation of a special wave-length, and the total area included under the curve is proportional to the total energy of all wave-lengths. By means of a pyrheliometer measurement the total energy of the rays for a unit area of surface and a unit of time is determined, and by dividing this numerical result of the pyrheliometer measurement by the area of the corrected bolograph a factor is obtained by which the total area of the bolographic curve at any stage or any fragment of it, whether as observed by the bolometer or as corrected to the limit of the atmosphere, may be multiplied to determine in absolute units the amount of energy corresponding to the conditions selected. It will be shown in the chapter on Sources of Error that a very moderate degree of accuracy in determining the transmission of the optical apparatus is sufficient for the purposes just stated.

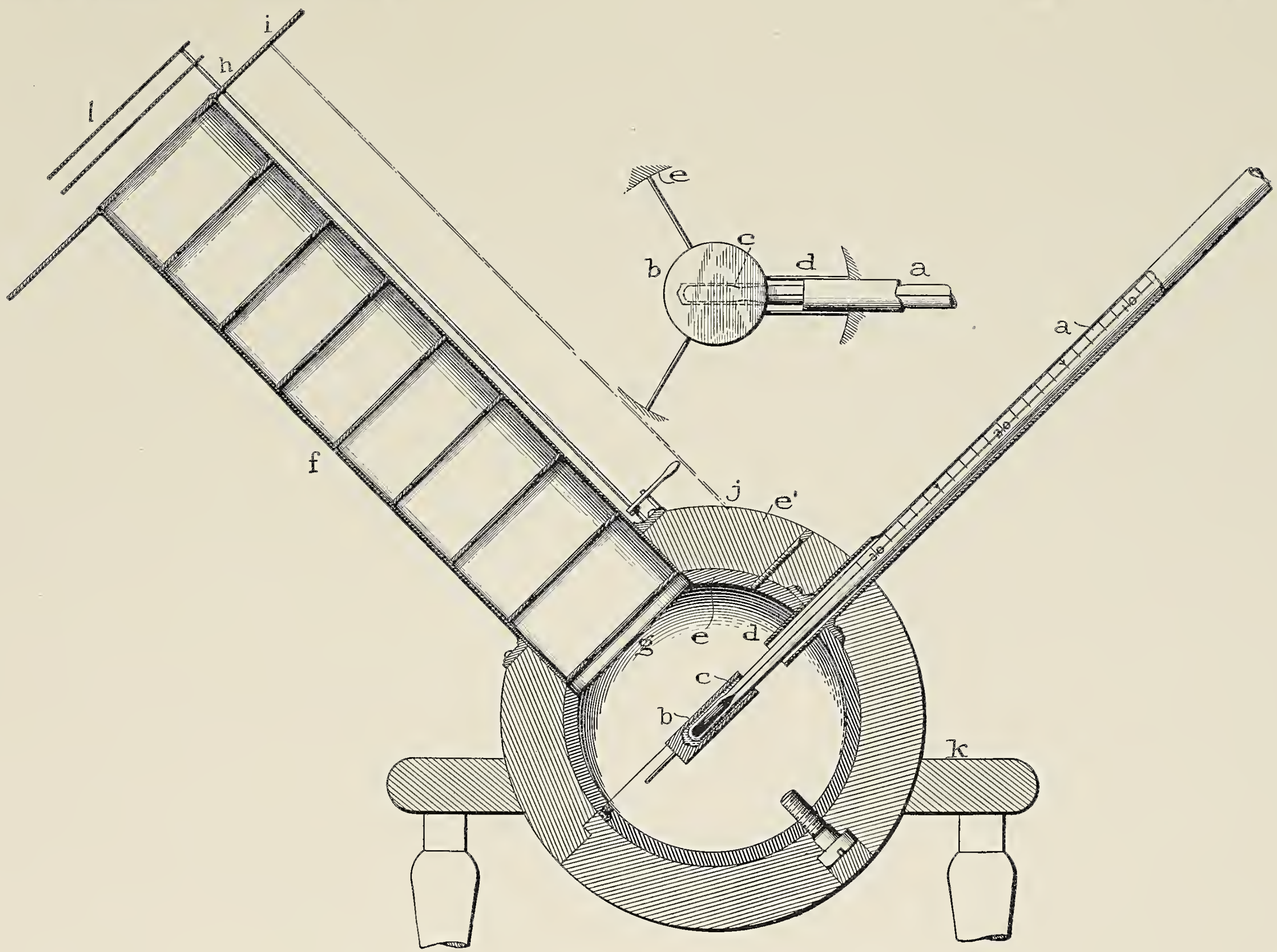
Four types of pyrheliometers and actinometers have been employed, including modifications of the mercury pyrheliometer, the Crova alcohol actinometer, the Ångström pyrheliometer,[1] and several modifications of a new type of continuously recording standard pyrheliometer. For reasons to be stated in the description of the last named, the first three of these types of instrument are regarded as secondary and not absolute instruments and as giving a nearly constant scale of energy, but not the absolute one.

MERCURY PYRHELIOMETER.

Pouillet's well-known pyrheliometer was improved by Tyndall by the substitution of mercury for water in the box which absorbs the radiation. Tyndall employed an iron box to contain the mercury, but since the conductivity of iron for heat is not very high, it is preferable to employ copper in place of iron. Furthermore, since the conductivity of copper is much greater than that of mercury, it is desirable to retain the mercury merely as a film about the bulb of the thermometer, to insure good contact between the box and the thermometer, instead of filling the box principally with mercury. In the preferred form[2] now employed in the work of the Astrophysical Observatory the pyrheliometer is of the design shown in Plate X. The cylindrical bulb of the thermometer *a* is immersed in mercury *c* within a small hole drilled in the side of the copper disk *b*. To prevent the weight of the disk *b* from breaking the slender neck of the thermometer, a brass tube *d* is provided, inclosing the thermometer, and from this tube *d* and from the metal case *e* the copper disk is supported by small stiff steel wires, as shown in the upper figure. The brass tube *d* is fixed to a hollow copper ball *e*, itself surrounded by the hollow spherical wooden case *e′*, through which the thermometer and inclosing tube pass. Solar radiation is admitted to the blackened front face of the copper disk *b* through the blackened tube *f*, which contains diaphragms (slightly smaller than the copper disk *b*) adapted to hinder air currents. The inmost diaphragm *g* is of a measured diameter somewhat smaller than the others, which increase in aperture from the

[1] The Ångström pyrheliometer was used by Mr. Kimball, of the Weather Bureau, during 1905 and is the property of the Weather Bureau.

[2] The first instrument of the kind employed at the Astrophysical Observatory was made at its shop in October, 1902. Until 1906 the box for absorbing radiation was always made thin, so as to be substantially a receptacle for mercury, but as now constructed the mercury is made use of only to insure good heat conductivity from the copper to the thermometer, as shown in Plate X. The introduction of the case *e* dates also from 1906.



Mercury Pyrheliometer.

inmost outward, so as to include a cone of rays of about $1\frac{1}{2}$ degrees. To avoid heating the wooden case, a zinc screen *h* is provided large enough to shade the entire ball *c′*. A small hole *i* admits a tiny beam of sunlight, which when falling on the mark *j* indicates that the instrument is correctly pointed toward the sun. The instrument is supported upon a ring stand *k*, in which it may be turned by the observer to face the sun at any angle. A light double-walled displaceable shutter of tin *l* is provided which is just large enough to shade the opening of the tube *f* when exposure to the sun is not desired.

Observations with the mercury pyrheliometer are made as follows: The instrument is placed so as to point toward the sun, but is shaded by the small shutter *l*, which, however, is adjusted so as to permit a guiding ray of sunlight to pass through the little hole *i*, that the instrument may be at all times kept pointing in the right direction. The thermometer is read and recorded each 20 seconds during the observations, which generally comprise intervals of two minutes each for exposures to the shade and sun alternately over a period lasting either ten or fourteen minutes. These periods suffice respectively for two or three determinations of the solar radiation at the earth's surface, and such groups of two or three determinations are made frequently throughout each half day of "solar-constant" work.

15000—08——4

The following is an example of one group of observations and reductions for this instrument:

TABLE I.—*Observations with mercury pyrheliometer.*

Station, Mount Wilson, California.
Date, June 14, 1905.
Observer with mercury pyrheliometer No. II, L. R. I.

Time.	Reading of thermometer.	Reduction. Temperature. Difference.	Reduction. Temperature. Rise per 20 seconds.	Time.	Reading of thermometer.	Reduction. Temperature. Difference.	Reduction. Temperature. Rise per 20 seconds.
$2^h21^m00^s$....	21°.54	....	....		25°.58	....	....
	.53	....	....		26 .21	+°.63	....
	.52	−°.01	....	28^m	.82	.61	....
22........	.52	.00	....		27 .41	.59	+.584
	.51	.01	....		.98	.57	.116
	.52	+ .01	....	29........	28 .50	.52	
23........	.54	+ .02	+.002		.64	....	.700
	22 .09	....	....		.49	− .15	3
	.80	+ .71	....	30........	.31	.18	
24........	23 .47	.67	....		.13	.18	2.100
	24 .11	.64	.658		.00	.13	....
	.74	.63	.039	31........	27 .88	.12	−.152
25........	25 .38	.64					
	.54	....	.697				
	.44	− .10	3				
26........	.36	.08					
	.29	.07	2.091				
	.21	.08	....				
27........	.14	.07	−.080				

Corrected rise per minute.	Time.
First exposure..............2.091	2^h24^m
Second exposure............2.100	2^h28^m

In order to obtain the last (and very important) reading of each two minutes without being distracted by another duty, the observer in each instance delays to begin to open or cover the instrument until he has read the thermometer; and on this account, if for no other reason, the rise of temperature during the first 20 seconds after opening or covering is not included in the reductions. This of course alters each result, but always in the same direction, so that as the instrument is regarded as a secondary and not a primary standard, the omission is found to introduce no sensible error.

Further discussion of the mercury pyrheliometer will be found in the chapter devoted to Sources of Error.

CROVA ALCOHOL ACTINOMETER.

Two specimens of the Crova alcohol actinometer have been used at the Astrophysical Observatory in Washington. Both instruments are by Duboscq and Pellin, Paris, and one of them was made with especial care under the valued supervision of M. Crova himself. The manner of using these instruments is identical with that of using the mercury pyrheliometer as described above, and their design is too well known to require description here. These two actinometers and three specimens of the mercury pyrheliometer were intercompared and served altogether as a multiple secondary standard of pyrheliometry, until the introduction in 1905 of the primary standard pyrheliometer about to be described.[1] One Crova instrument was broken, unfortunately, so that it has been of little service. In 1906 several specimens of the mercury pyrheliometer, as improved, were compared with the earlier instruments and with the standard pyrheliometer, and are now used almost exclusively. Additional facts relating to these instruments will be found at the conclusion of this chapter and in the chapter on Sources of Error.

PRIMARY STANDARD PYRHELIOMETER.

Many forms of apparatus for measuring the solar radiation have been devised since the time of Pouillet, which have this in common, that the radiation falls upon a front, or outer, blackened absorbing surface behind or within which is situated a thermometer or other temperature indicator, whose readings form a principal part of the record. Recognizing that the blackened surface is not a perfect absorber, it is customary to make a correction of from 3 to 5 per cent for the loss of radiation by reflection. Three principal methods of reading are in vogue: (1) In a body of measured heat capacity the rate of rise of temperature due to the absorption of radiation is noted, and the loss or gain of heat to the surroundings is allowed for by cooling corrections obtained immediately before and after exposure to the sun. An example of this method of reading has already been given. (2) In a body of measured heat capacity the rate of rise of temperature due to absorption of radiation is observed, together with data assumed to indicate what rate of rise corresponds to the state when the body neither gains nor loses heat to the surroundings. This method is employed in different ways in the actinometer of Violle, and in the silver disk actinometer devised by Nichols and Hull for their experiments on the pressure due to radiation. (3) Two bodies of similar form are heated, one by absorbed solar radiation, the other by a known source of heat δ. Means are provided to indicate when the temperatures of corresponding points on the surfaces of the two bodies are equal, and then the heat of absorbed solar radiation is assumed to be equal in amount to that introduced from the known source of heat. This is the principle of the Ångström compensation pyrheliometer.

[1] Comparisons were also made by Mr. Kimball, of the Weather Bureau, between these instruments and several copies of the Ångström compensation pyrheliometer.

As further discussed in the chapter on Sources of Error, there is a certain source of error in all these types of apparatus due to the fact that when the radiation is absorbed upon the front or outside blackened surface, two paths are open to the heat produced in the absorbing material. This heat will in part be conducted backward or inward toward the temperature-indicating apparatus, but will in part be convected and radiated outward and away from the temperature-indicating apparatus. The latter part, though small, can not be readily determined and is likely to be variable during a day of observation, depending on the wind, the inclination to the horizontal, and on the distribution of temperature near the instrument.

A new form of pyrheliometer has been devised and constructed at the Astrophysical Observatory to avoid the sources of error just noted. As is often the case with new apparatus, it has been developed through several preliminary forms, and though these may be mentioned briefly, it is only the last constructed form which needs to be particularly described.

In this attempt to devise a standard pyrheliometer, which was begun in 1903, the point of departure from the forms of pyrheliometer in general use lies in the adoption of a hollow absorbing chamber to receive the solar rays. Such a chamber with a small aperture at the entrance has, as is well known, approximately the properties of the "absolutely black body," and is an approximately perfect absorber. Consequently no correction is needed for the reflection of rays from the receiving surface. At the time when the attempt to devise a "black body" pyrheliometer was begun the writer was not aware that this principle had ever been used in pyrheliometry; but it had in fact been employed since 1894 by V. A. Michelson in a pyrheliometer involving also the method of measurement of the Bunsen ice calorimeter.[1]

It was first intended here to receive the rays in a long, curved, conical tube like a horn in shape, and to construct the sides of this horn of several layers of platinum resistance tape insulated from one another by the thinnest of silk cloth of known water equivalent. For theoretical and practical reasons this form was abandoned after being partially constructed.

In the next form tried the receiving chamber was of the form of a test tube, and its walls were composed of thin steel tubing wound upon a mandril and soldered together so as to remain in the proper shape after the mandril was withdrawn. A current of mercury was caused to flow through the apparatus so as to carry off the heat produced by the solar rays; and the resistance of definite lengths of the mercury stream before and after passing the chamber was measured by the aid of platinum electrodes sealed into glass tubes which formed continuations of the steel coiled tube. The main defects of this apparatus proved to be, first, too great a

[1] V. A. Michelson, Russkoe fisiko-kimicheskoe obshchestvo zhurnal, St. Petersburg, 1894, XXVI, pt. 1, 1–25.

capacity for heat in the steel tubing, so that the apparatus responded but sluggishly to solar radiation, and, second, the passage of bubbles in the mercury stream, which disturbed the steadiness of the resistance measurements. It will be noted that in this method of observation a continuous calorimetry was proposed analogous to that perfected for other uses by Callendar and Barnes. Owing to the defects mentioned, the mercury stream pyrheliometer was abandoned after trial.

It was next proposed to obtain a double-walled glass receiver of the form of a test tube between whose walls should flow a stream of water, and to measure the rise of temperature of the water by a platinum resistance thermometer. On inquiry it was found impossible to obtain the glass parts in the desired form.

There was next constructed at the observatory shop a double-walled test-tube-shaped receiver of German silver, to which glass tubes were attached to provide for the flow of nitro-benzol round between the walls, starting from the front, near the place of entrance of the solar rays, back to the conical rear end, where the rays were principally absorbed, and thence away. Platinum resistance wires were inserted in these glass tubes, and the rise of temperature of the liquid was determined by the Wheatstone bridge method. A coil of platinoid wire of measured resistance was wound in a spiral form between the walls of the German silver chamber, partly to guide the flow of liquid, but chiefly to enable a known quantity of heat to be produced electrically; and this being measured as if it were solar heating, the behavior of the instrument could thus be ascertained. The results were so far satisfactory that it was believed that complete success was now near. Among other details of experience with this instrument it was found that very great care must be taken to supply the liquid current at the most constant possible rate and temperature; for the maximum safe rise of temperature of the liquid due to the absorption of solar radiation appeared to be only about 0°.1 centigrade, and to obtain a measurement of this quantity to one per cent requires very steady electrical and thermal conditions. If a more considerable rise of temperature is allowed, there is danger of loss of heat by conduction through the outside wall of the apparatus. The liquid nitro-benzol was chosen in preference to water, partly because a safer insulator, but chiefly because the quotient of its specific heat by its specific gravity is only about 0.4 as great as with water, so that the rate of flow can be considerably greater and proportionately more uniform. In order to employ it for this purpose, determinations of the properties of nitro-benzol were made which resulted as follows:

Specific heat of nitro-benzol.

Temperature.	Specific heat.
14° C.	0.3500
28° C.	0.3620

Between these temperatures the specific heat of nitro-benzol increases nearly uniformly, as shown by numerous determinations.

The preliminary constructions and experiments just described were made in the autumn and winter of 1903–4; and having proved promising on the whole, plans were made for an automatic, continuously recording, standard pyrheliometer to be constructed along similar lines. An equatorial mounting and clock by Brashear were available. Apparatus for providing and measuring a flow of liquid at constant rate (for which water was now chosen instead of nitro-benzol) was furnished in 1904 by the International Instrument Company, of Cambridge, Mass. The pyrheliometer proper, with the mechanical adjuncts for adjusting and standardizing the platinum resistance thermometer, was constructed in the Observatory shop, and the electrical parts were inserted and measured at the Observatory.

Figure 1, Plate XI, may be referred to in connection with the following description: The receiving chamber *a* is of cylindrical shape with a conical portion at the rear on which the solar rays fall. Diaphragms are inserted to hinder the loss of heat by convection, and the whole interior of the chamber is blackened with lampblack. Rays not absorbed at first incidence upon the conical portion, and rays emitted from the conical portion in consequence of its rise of temperature, will be reflected to and fro within the chamber and will be at length almost completely absorbed somewhere upon its walls. The solar rays enter the chamber through a blackened tube *b*, also provided with diaphragms *c*, of which the one nearest the entrance of the chamber is the smallest, and is of carefully measured aperture. A double flap shutter *g g*, operated by a linkage *h*, is adapted to cut off the solar rays when closed, and may be operated by the action of an electromagnetic device. Outside the absorbing wall of the chamber *a* is a second wall *d*, and at the rear this outer wall is in its turn inclosed in a double-walled jacket *l*. Through a tube e_1 a current of water enters the outer jacket in a tangential direction, passes thence by a spiral tube to the front of the space between the walls of the chamber, and after circulating about between the walls, passes out through the tube e_2. At $f_1\ f_2\ f_3\ f_4$ are inserted four fine platinum wires, which are connected to form a Wheatstone bridge, and serve with other necessary adjuncts to determine the rise of temperature of the water due to the heating of the chamber. In order to check the accuracy of the results, a coil of wire *m* of measured resistance is inserted in the chamber near the rear, and through this a known current of electricity may be passed, thus producing therein a known amount of heat. This heat is determined in the flowing water as if it were from the sun, and the accuracy of the measurements are judged by the approximate equality of "heat found" to the "heat introduced."

Figures 2 and 3 show diagrams of the electrical circuit, by means of which the rise of temperature of the water is observed. Figure 2 gives a more simple view

Fig. 1.

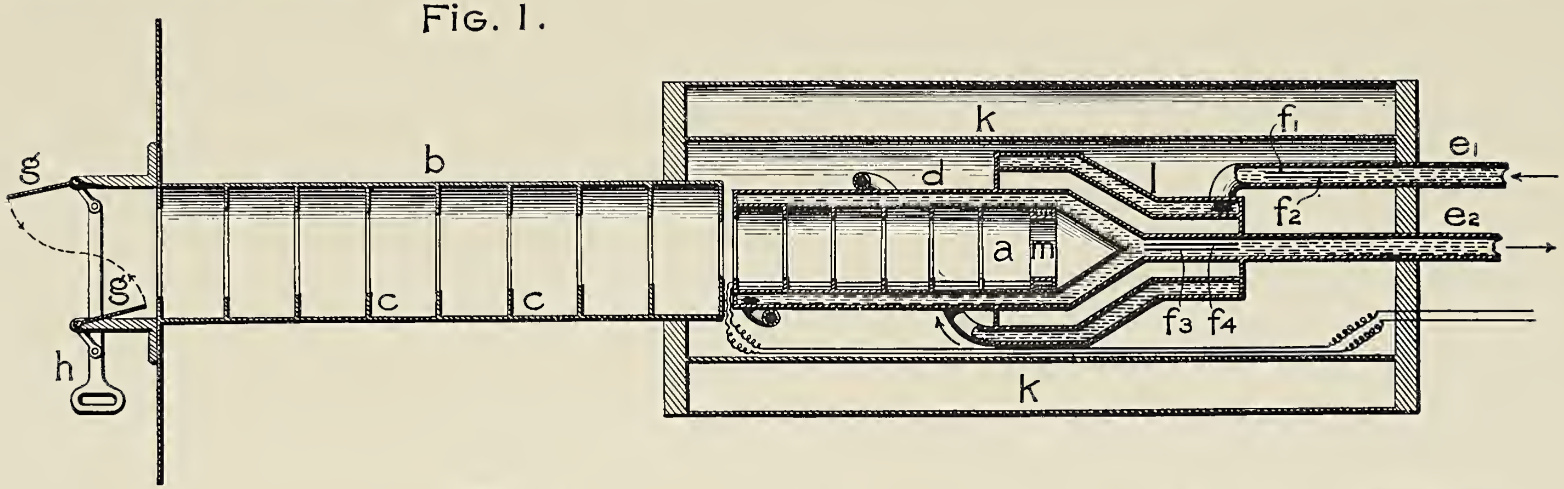


Fig. 3.

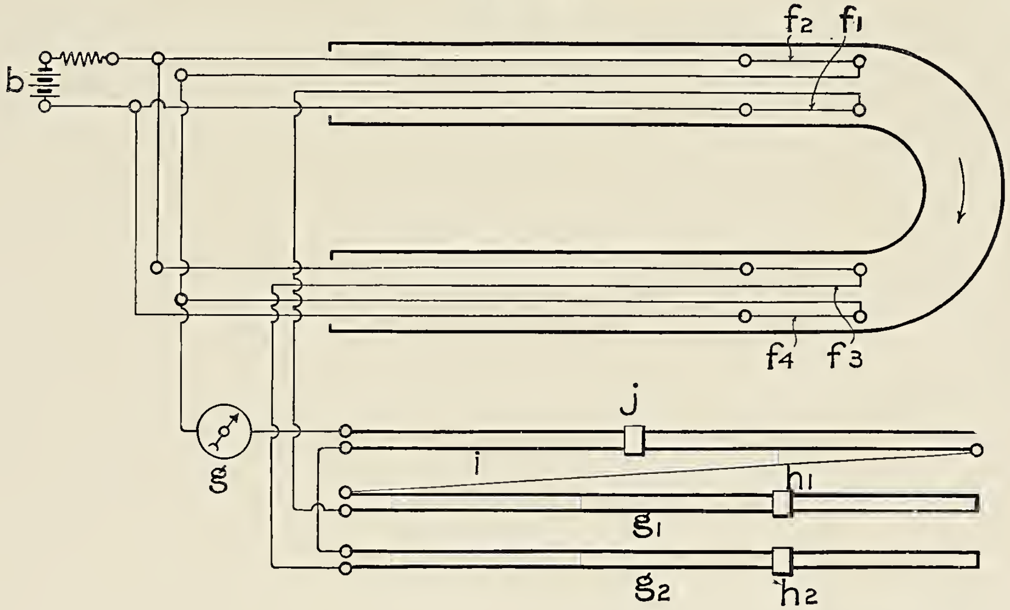
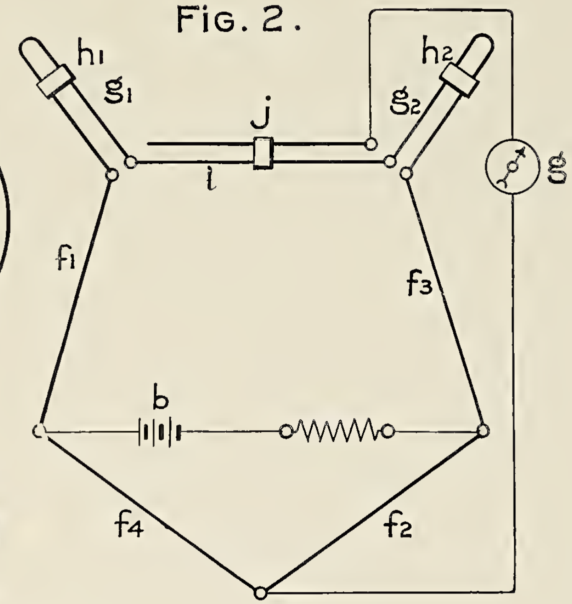
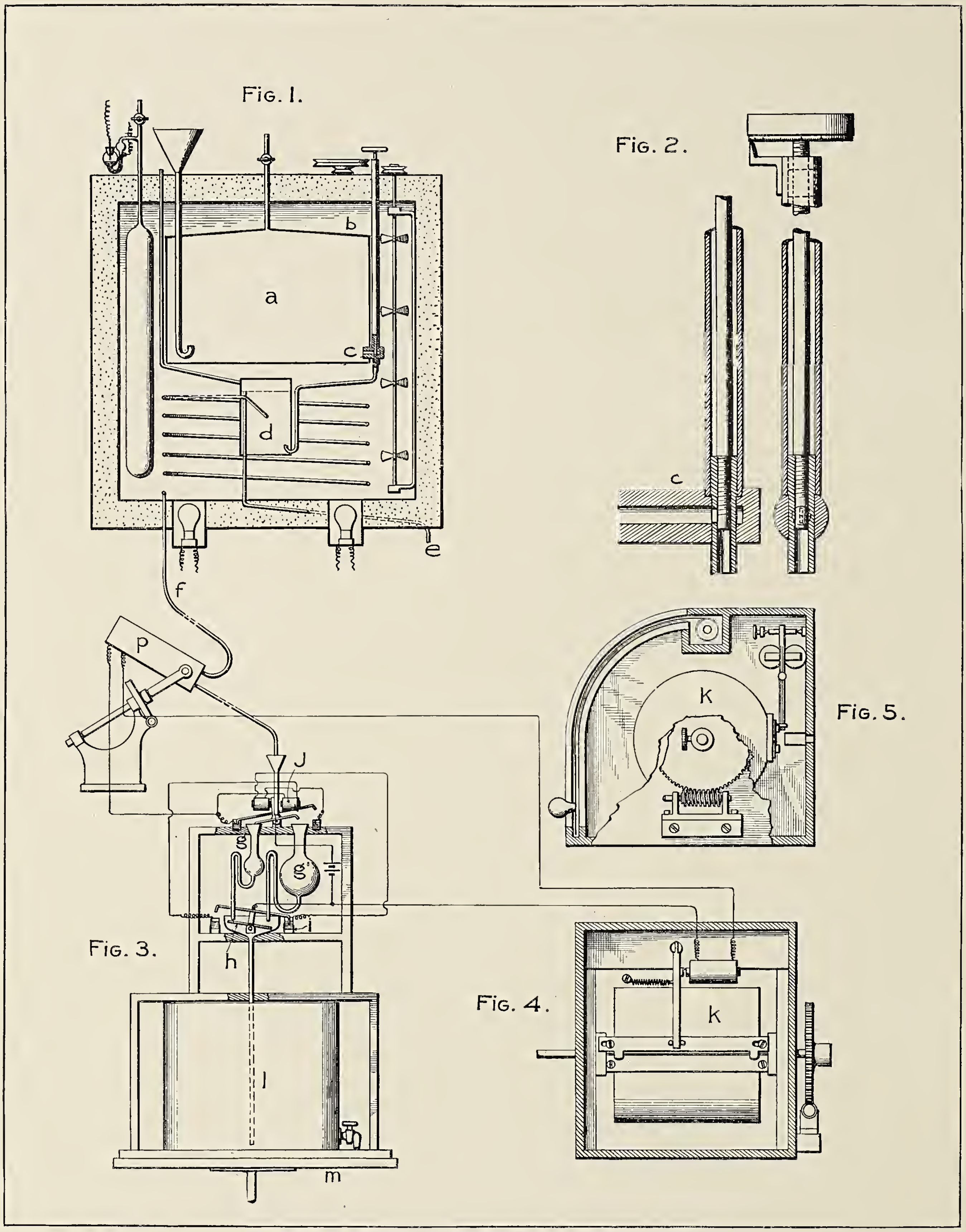


Fig. 2.



Continuous-flow Standard Pyrheliometer.



Adjuncts to the Continuous-flow Standard Pyrheliometer.

of the circuit which shows that it is arranged with the most perfect possible symmetry and consists of the battery B, galvanometer G, four platinum resistances $f_1 f_2 f_3 f_4$, two looped slide wires g_1 and g_2, with shunting contacts h_1 h_2 to alter the resistances of these loops, and plain slide wire i, with sliding galvanometer contact j. Figure 3, similarly lettered, shows with more detail how the circuit is introduced to measure the rise of temperature of the current of water in which it is immersed. In the actual instrument the three slide wires are placed between the inner and outer walls of a cylindrical case k, which surrounds the pyrheliometer chamber, and the sliders are of the form used with the bolometer, as shown in Plate VIII, and are moved by screws operated from outside the case. The resistances of the several parts of the circuit are as follows:

$$f_1 = f_2 = f_3 = f_4 = 3.4\Omega \qquad g_1 = g_2 = 0.15\Omega \qquad i = 0.006\Omega$$

Battery current usually 0.02 amperes.

Diagrams of the apparatus for supplying the flow of water are shown in Plate XII. Referring to figure 1, the water is contained in a Marriotte's bottle a, immersed in a tank of water b, which may be stirred and regulated at a constant temperature in the same manner as the baths commonly employed by chemists. From the Marriotte's bottle the water flows through a valve c of the construction indicated in figure 2 to a reservoir at atmospheric pressure d. This is provided with an overflow tube e and a worm-shaped discharge tube f, and the flow of water from the Marriotte's bottle a is regulated so that a little water will always be dripping from the overflow tube, so that the level in the reservoir d will remain constant. After passing through the pyrheliometer (indicated at P) in the manner already related, the water flows through a second micrometer valve (omitted in the diagram) like that shown in figure 2, which is situated at a higher level than the pyrheliometer P, though lower than the reservoir a. Thus the water flows between constant levels as regulated by a micrometer valve, and no variations of rate of flow have ever been detected with certainty.

Figure 3, Plate XII, shows the method of measuring the rate of flow of water. Being conducted from the outflow tube, the water falls upon a trough, which guides it into a syphon g. When full this syphon discharges upon a lever h, and thereby turns it upon its fulcrum so as to break contact in a mercury cup i, thereby causing the electromagnet j to tip the trough in a manner to fill the second syphon g. By similar actions the syphons alternately fill and discharge and record the times by electrically controlled light action on a moving photographic film wound on the drum k, shown in figures 4 and 5. At the same time the water is all collected in the reservoir l, which stands upon a scale pan m, and may be weighed from time to time to check the results.

Figures 4 and 5 show the photographic recording apparatus for registering the indications of the galvanometer as to the temperature of the platinum thermometer, and also the flow of the water as indicated by the syphon apparatus.

The pyrheliometer itself was mounted equatorially and driven by clockwork so as always to point toward the sun. Its shutter was closed by an electromagnet at each time the smaller syphon filled with water, thereby indicating on the galvanometer record the position of zero radiation.

In this form the instrument was tried repeatedly on Mount Wilson during the summer of 1905, and at first with very indifferent success, as indicated by a lack of agreement between "heat introduced" and "heat found," in the experiments with the electrically heated coil. The defective action was soon found to be caused by irregularity in the path of flow of the water between the walls of the chamber, and by an unsatisfactory method of insulating the platinum thermometer wires from the sides of the water tubes. Late in August, 1905, the method of inserting the thermometer wires was improved, and a spiral copper wire about 8 feet long was wound between the walls of the chamber so as to guide the water in a long spiral course in its flow. Very great improvement resulted from these changes, and on several different days thereafter measurements were made in which the "heat found" was between 95 and 100 per cent of "heat introduced."[1] The principal defect then seemed to be the uncertainty of contacts upon the slide wire used for determining sensitiveness, so that the different experiments were less concordant than could be hoped.

In 1906 the instrument was again tried on Mount Wilson, but a new way of determining the sensitiveness was employed. Instead of the unsatisfactory slide-wire method, a shunt resistance of nearly 700 ohms was placed in parallel with one arm of the Wheatstone bridge, and portions of this shunt of 15, 30, and 60 ohms respectively were made removable at pleasure, so as to produce a calculable change in the resistance of this arm of the Wheatstone bridge. This device proved to act as well as could be desired, and removed all uncertainty in measuring the sensitiveness. Another source of error was found to be connected with the disturbing action on the galvanometer of the electromagnets used in the apparatus for measuring and recording the flow of water. These were dispensed with, and even the shutter for shading the pyrheliometer was operated by hand, so as to avoid all danger of the kind. Under these conditions the heating effect in the coil was measured on numerous days, with various rates of water flow, and with many angles of inclination of the pyrheliometer to the horizon, and in numerous experiments between 99 per cent and 100 per cent of "heat introduced" was "heat found." Nothing could have exceeded in satisfactory behavior this complicated apparatus during these trials, and on the same days

[1] In an account given by C. G. Abbot in New York in 1905 the results were given as from 97 to 103 per cent, but an error of calibration of the platinum thermometer was found later which altered the result slightly.

comparisons were made between the indications of this pyrheliometer and those of the two secondary instruments ordinarily employed to measure the radiation of the sun. A summary of these observations is given below.

TABLE 2.—*Observations with standard pyrheliometer.*

Date: August 22, 1906.
Rate of flow of water in standard pyrheliometer, 53.45 grams per minute.
Electrical heating. Comparison of heat introduced with heat found.

Time.	Calories per minute.		Difference in per cent.
	Heat introduced.	Heat found.	
$2^h\ 30^m$	2. 502	2. 496	−0. 2
2 35	2. 492	2. 476	−0. 6
3 18	2. 492	2. 510	+0. 7

Date: August 23, 1906.
Rate of flow of water in standard pyrheliometer, 64.3 grams per minute.
Electrical heating. Comparison of heat introduced with heat found.

Time.	Calories per minute.		Difference in per cent.
	Heat introduced.	Heat found.	
$2^h\ 58^m$	2. 508	2. 510	+0. 1
4 3	2. 500	2. 520	+0. 8

Solar heating. Comparison with mercury pyrheliometer No. II.

Time.	Calories per square centimeter per minute.	Corrected reading of pyrheliometer II.	Constant of pyrheliometer II.
$1^h\ 59^m$	1. 576	2. 113	0. 746
2 37	1. 568	2. 090	0. 750
3 47	1. 494	1. 962	0. 761

Solar heating. Comparison with mercury pyrheliometer No. IV.

Time.	Calories per square centimeter per minute.	Corrected reading of pyrheliometer IV.	Constant of pyrheliometer IV.
$2^h\ 19^m$	1. 605	1. 793	0. 895
3 9	1. 465	1. 722	0. 856
4 21	1. 403	1. 568	0. 895

Date: August 31, 1906.
Rate of flow of water, 63.9 grams per minute.
Electrical heating.

Time.	Calories per minute.		Difference in per cent.
	Introduced.	Found.	
$5^h\ 12^m$	2. 424	2. 405	−0. 8

TABLE 2.—*Observations with standard pyrheliometer*—Continued.

Solar heating. Comparison with pyrheliometer II.

Time.	Calories per square centimeter per minute.	Corrected reading of pyrheliometer II.	Constant of pyrheliometer II.
4^h 13^m	1.258	1.696	0.742
4 38	1.197	1.564	0.765
4 52	1.119	1.488	0.752

Solar heating. Comparison with pyrheliometer IV.

Time.	Calories per square centimeter per minute.	Corrected reading of pyrheliometer IV.	Constant of pyrheliometer IV.
3^h 54^m	1.281	1.450	0.884
4 36	1.220	1.376	0.886

From these figures it appears that, irrespective of a variation of 20 per cent in the rate of flow of the water current, the "heat found" differed not at all on the average in three different days of observation from the "heat introduced."

The constant of pyrheliometer No. II comes out as 0.753±0.003 and that of pyrheliometer No. IV appears as 0.883±0.005, or, if we reject one discordant observation, as 0.890±0.002.

On the provisional multiple scale of pyrheliometry employed in preliminary publications since 1903 the constants of the two pyrheliometers were given as 0.764 and 0.902, respectively. Accordingly the provisional scale of pyrheliometry used by the Astrophysical Observatory from 1903 to 1906, both at Washington and Mount Wilson, appears from these results to be about 1.4 per cent above the absolute scale. This apparently well-verified conclusion was very embarrassing, because through measurements of Mr. H. H. Kimball, of the United States Weather Bureau, and others of Mr. L. R. Ingersoll, of the University of Wisconsin, comparisons had been made between the Astrophysical Observatory provisional scale and that of the Ångström compensation pyrheliometer, as exemplified by the instruments of the Weather Bureau and those of the University of Wisconsin. In these comparisons the Ångström scale (recognized as standard by the International Union for Cooperation in Solar Research) had been found nearly 15 per cent lower than that of the Astrophysical Observatory;[1] and though the Ångström pyrheliometer necessarily reads too low, as pointed out on an earlier page, so large

[1] In these comparisons the older type of Ångström pyrheliometer having platinum strips was employed. This type reads too low on account of the change of resistance of platinum, as shown by Callendar. Recently a careful comparison has been made with a new Ångström pyrheliometer having manganin strips, now in possession of the Weather Bureau. This instrument is in good accord with another of the same type, also at the Weather Bureau. The result of the comparison shows that the readings of our continuous-flow pyrheliometer are 1.092 times the readings of the Ångström.

a discrepancy between this and the absolute scale was unexpected and led to distrust of the results of the continuous-flow pyrheliometer.

Referring to figure 1, Plate XI, it will be seen that there is a defect of design of this instrument which tends to produce too high results; for the water after being warmed by the sun and having passed the wires f_3f_4 still flows for a short distance inside the outer protecting jacket, which tends to warm the water after its temperature has been tested by the wires f_1f_2. But the distance is so short and the linear rate of flow so rapid that it seems hardly possible that this defect of design could produce injurious effects of any consequence; and if it did so this source of error would effect measurements of electrical heating as much as those of solar heating. It is perhaps possible that an appreciable portion of the electrically supplied heat escapes by convection from the front of the chamber, and that this loss of heat is compensated by some sources of error which, like that just noted, tends to make the readings too high. Inasmuch as the solar heating is more favorably applied than that of the resistance coil, a smaller proportion of solar heat would be lost by convection, and thus the readings might actually be too high, notwithstanding the apparent check upon them furnished by supplying and measuring a known amount of heat. This possible state of affairs is, however, rendered very improbable by the fact that the agreement between "heat applied" and "heat found" was independent of the rate of flow of the water, and it is certain that the loss of heat by convection must diminish when the rate of flow is increased.

But although the scale of pyrheliometry furnished by the continuous-flow instrument used on Mount Wilson in 1906 appears to be so thoroughly verified, yet its discrepancy (9.2 per cent) with Ångström's scale is so great and the securing of an absolute scale is so important that a new continuous-flow pyrheliometer is now being constructed of greatly improved design and with very different dimensions. When complete it will be carefully compared with its predecessors.

The results given in the present volume are on the arbitrary multiple pyrheliometer scale heretofore adopted by this Observatory and are to be diminished by 1 part in 74, if reliance can be placed on the standard pyrheliometer comparisons of 1906. Until entire assurance of this can be had it seems undesirable to apply this small correction.

COMPARISON OF SECONDARY PYRHELIOMETERS.

The following table includes the results of all the simultaneous readings of pyrheliometers and actinometers made since 1903 to determine their relations to the multiple scale of pyrheliometry just referred to. In adopting the values of the ratios and the final values of the constants of the pyrheliometers some exercise of judgment was made as to the weights of the several observations, and it is possible that another observer, in discussing the material, would have arrived at values slightly different. But it is believed that in no case would a change of more than a small fraction of 1 per cent be thought advisable. As will be noted, there is considerable discordance in the comparisons in which the Crova actinometer figures, doubtless on account of the great change of the specific heat of alcohol with changing temperature. Since the constant of pyrheliometer No. I prior to October, 1904, depends on the Crova instrument, there must be allowed an uncertainty of, perhaps, 2 per cent in its value. It is believed that there is no uncertainty as great as 1 per cent in the comparisons of the instruments employed in 1905, 1906, and 1907.

TABLE 2A.—*Comparisons and constants of secondary pyrheliometers.*

WASHINGTON COMPARISONS.

Feb. 24, 1903. Ratio $\frac{I}{Crova}$	0.5087	0.4888	Nov. 25, 1905.	0.5210	1.0992	1.0581	1.0939
0.5505	.5166	.49385	0.4825	.4959	1.0753	1.0575	1.1117
.5769	.50897	Nov. 23, 1905.	.4869	.5394	Apr. 17, 1906. Ratio $\frac{I}{IV}$	1.0588	1.0978
.5181	May 24, 1905.	0.4737	.5031	.5114	1.0929	1.0475	1.0912
.54850	0.4903	.4900	.5049	.4874	1.1268	1.0401	1.0979
Feb. 25, 1903.	.5012	.4877	.4866	.5224	1.1276	1.0478	Apr. 17, 1906.
0.5283	.5333	.5311	.4988	.50932	1.1158	Apr. 2, 1906. Ratio $\frac{I}{VI}$	1.1227
.5358	.50827	.5038	.4865	May 4, 1905. Ratio $\frac{II}{Crova}$	Apr. 4, 1906. Ratio $\frac{I}{V}$	1.0259	1.1299
.5542	* June 3, 1905.	.5149	.5428	0.5477	1.0151	1.0290	1.1053
.5483	0.5273	.4972	.5151	.5276	1.0429	1.0145	1.1162
.5681	.5308	.4918	.4845	.5642	1.0710	1.0174	1.1066
.54694	.5220	.4962	.4850	.5639	1.0430	1.0486	1.0791
* Dec. 1, 1903.	.52670	.4934	.5654	.55085	Apr. 17, 1906.	1.0271	1.1100
0.5326	Nov. 4, 1905.	.4990	.5281	May 1, 1905 Ratio $\frac{II}{I}$	1.0283	Apr. 2, 1906. Ratio $\frac{V}{IV}$	Apr. 18, 1906.
.5296	0.5217	.4985	.4981	1.1065	1.0430	1.0836	1.0809
.5311	.4756	.4800	.5286	1.0458	1.0398	1.0512	1.0897
† Dec. 16, 1904.	.5141	.5093	.5050	1.0761	1.0748	1.0571	1.0968
0.5153	.4834	.5059	.4928	May 2, 1905.	1.0512	1.0819	1.0827
.5153	.4853	.5054	.4875	1.0588	1.0433	1.0287	1.0931
.4942	.49602	.4927	.4928	1.0833	1.0416	1.0665	1.0767
.4911	Nov. 17, 1905.	.4922	.5370	1.0661	1.0460	1.0615	1.0866
.4939	0.4821	.4794	.4909	1.0594	Nov. 22, 1906.	Apr. 4, 1906. Ratio $\frac{VI}{IV}$	Apr. 17, 1906. Ratio $\frac{VI}{V}$
.4929	.4966	.5038	.4865	1.0952	1.0395	1.0900	1.0409
.50045	.5050	.5028	.4963	1.0484	1.0331	1.1029	1.0256
May 2, 1905.	.4878	.5209	.5088	1.0924			1.0280
0.5016	.5020	.5143	.5231				1.0315
	.5068	.5027	.5050				
	.4817	.5106	.50472				
		.5012	Apr. 18, 1906.				
		.5000	0.4995				
		.49994	.4976				

MOUNT WILSON COMPARISONS.

Aug. 9, 1905. Ratio $\frac{II}{III}$	Sept. 6, 1905.	1.2003	Aug. 31, 1906.	1.1608	1.1038	1.1095	1.1213
1.0251	0.9933	1.1776	1.1588	1.1649	1.1220	1.0773	1.0925
1.0201	0.9933	June 19, 1906.	1.1689	1.1833	1.0863	1.0885	1.0987
1.0170	1.0157	1.1941	1.1786	1.1493	1.1026	1.1006	1.1294
0.9884	1.0120	1.1691	1.1688	1.1639	1.1090	1.0764	1.1010
1.0126	1.0036	1.1722	Sept. 5, 1906.	*Sept. 10, 1906.	Aug. 31, 1906.	1.0972	1.1128
Aug. 11, 1905.	Sept. 7, 1905.	1.1513	1.1678	1.1946	1.1087	1.0918	1.1110
1.0148	1.0150	1.1502	1.1621	1.1868	1.0923	1.1012	1.1227
1.0044	1.0075	1.1755	1.1583	1.2020	1.1098	1.0928	1.1093
1.0191	1.0112	1.1790	1.1706	1.1867	1.0850	1.1016	1.1068
1.0236	Oct. 24, 1905.	1.1784	1.1495	1.1912	1.0982	1.0693	1.1150
1.0219	1.0007	1.1617	1.1519	1.2067	1.0952	1.1005	1.0992
1.0059	1.0202	1.1881	1.1831	1.1831	1.0995	1.0808	1.1159
1.0218	1.0104	1.1500	1.1496	1.1908	1.0888	1.0915	1.1073
1.0393	Sept. 10, 1906.	1.1618	1.1724	1.1894	1.0825	Sept. 5, 1906.	June 19, 1906. Ratio $\frac{II}{VI}$
1.0229	1.0233	1.1430	1.1625	1.1569	1.1016	1.0990	1.0448
1.0404	1.0163	1.1482	1.1485	1.1888	1.1038	1.0976	1.0486
1.0573	1.0198	1.1659	1.1489	†Oct. 18, 1906.	1.0918	1.0916	1.0695
1.0191	*June 16, 1906. Ratio $\frac{II}{IV}$	July 10, 1906.	1.1604	1.1604	1.0839	1.0961	1.0567
1.0275	1.1839	1.1883	Sept. 6, 1906.	1.1763	1.1049	Sept. 6, 1906. ‡Ratio $\frac{VI}{IV}$	1.0707
1.0254	1.1642	1.1568	1.1922	1.1865	1.0966	1.0967	1.0727
1.0191	1.1785	1.1636	1.1651	1.1744	1.0962	1.1268	1.0605
1.0242	1.1802	1.1739	1.1786	June 19, 1906. Ratio $\frac{VI}{IV}$	Sept. 4, 1906.	1.0960	
Aug. 24, 1905.	1.1758	1.1706	Sept. 7, 1906.	1.1166	1.0969	1.0893	
1.0235	1.1600	Aug. 21, 1906.	1.1744	1.1292	1.0893	1.0994	
1.0204		1.1570	1.1599	1.0929	1.0959	1.1039	
1.0048		1.1597	1.1609	1.1188	1.0975	1.0973	
1.0063		1.1583	1.1574		1.0908		
1.0138					1.0810		

ADOPTED RATIOS.

Washington observations. Old I / Crova	New I / Crova	New I / IV	New I / V	New I / II
0.5444	0.5048	1.1132	1.0482	0.9296

Mount Wilson observations. II / III	From June to Sept. 9, 1906. II / IV	After Sept. 9, 1906. II / IV	Prior to Sept. 6, 1906. VI / IV	On and after Sept. 6, 1906. VI / IV
1.0137	1.1683	1.1847	1.0997	1.1073

ADOPTED PYRHELIOMETER CONSTANTS.

No. IV	0.9020
Old I	.7524
New I	.8102
Crova	.4096
No. V	.8479
§ No. II	.7640

* Pyrheliometer II became dusty on its blackened surface (probably during the winter 1905–6). Dust removed Sept. 9, 1906.
† Not strictly simultaneous readings. Allowed one-half weight.
‡ Pyrheliometer VI was newly blackened on Sept. 6, 1906.
§ Pyrheliometer II was used on Mount Wilson in 1905. From Washington observations its constant would be 0.753; from Mount Wilson observations of early 1906, 0.772; of late 1906, 0.7614.

Chapter III.

SAMPLE OBSERVATIONS AND COMPUTATION OF SOLAR RADIATION OUTSIDE THE ATMOSPHERE.

The methods employed for determining the distribution of radiation in the solar spectrum, for estimating the transmission of the atmosphere, the cœlostat, and the spectroscope, for determining the ratio of the solar radiation outside the atmosphere to that at the surface of the earth, and the means employed for measuring the latter have been explained in Chapters I and II. The present chapter will be devoted to illustrating in detail the measurements and results obtained on a single day of observation.

On August 8, 1906, the following series of observations was made to determine the value of the "solar constant" of radiation. The result of the day's observations has about the average weight of good grade Mount Wilson work, although the bolometric observations in two instances required larger corrections for change of sensitiveness than usual, and although the transmission of the atmosphere appeared to be not quite steady. The day is chosen because all the correcting factors were determined, including transmission of spectroscope and reflecting power of cœlostat. As these factors are of secondary importance, they are not determined every day, but are usually supplied by computation from the known general form of the solar energy curve outside the atmosphere.

Station, Mount Wilson, California.
Date, August 8, 1906.
Sky cloudless, but somewhat milky.[1]
Observer at spectrobolometer, C. G. A.
Observer at pyrheliometer, L. R. I.

SPECTROBOLOMETRIC OBSERVATIONS.

Current of battery, 0.08 ampere.
Bolometer, 12 mm. × 0.06 mm. Resistance, 4 ohms.
Slit of principal spectroscope, 100 mm. × 0.5 mm.
Effective height of slit: First 3¼ minutes, 100.
Next 2½ minutes, 30.7.
Next 3¾ minutes, 12.4.
Rest of run, 100.
Shutter inserted for 5-second intervals after 0, 1, 2, 3, 4, 5, 6, 7¼, 8, 9½, and 11 minutes.
All bolographs start at counter reading 186′ 0″. The "A" line at 200′ 0″.
In 1 minute of time counter turns 2′, spectrum moves 40′ of arc, and plate moves 4 centimeters.

[1] The haziness during 1906 was generally in excess of that observed in 1905.

Bolographs taken as follows:[1]

TABLE 3.—*Spectrobolometric observations.*

Number.	Plate.	Apparent solar time of start.	Distance of trace from side of plate at start.	Total drift.	Counter at close.	Remarks.
		a. m.	*c. m.*			
1	I	6 48	1	1 cm. N.	208′ 30″	
2		7 00	2	½ cm. S.	209 0	
3	Plate reversed	7 16	1	0	209 0	
4		8 10	2	0 (?)	209 30	
5	II	8 31	1	2 cm. S.	208 30	Substitute mirrors.
6		8 48	2	2 cm. S.	209 30	
7	Plate reversed	9 10	1	1½ cm. S	208 30	4 mirrors.
8		9 26	2	0	209 0	
9	III	9 46	1	2 cm. S.	208 30	4 mirrors.
10		10 01	2	0	209 0	
11	Plate reversed	10 18	1	2 cm. S.	208 30	Substitute mirrors.
12		10 33	2	....	209 0	

[1] To economize plates, four bolographs are generally placed on each plate, two running one way, two the other. To avoid confusion, only two curves are shown in illustration, Plate XIII.

TABLE 4.—*Observations for determination of transmission of spectrometer.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.
Setting of small spectroscope.	Setting of large spectroscope.	Bolometer.					Deflection A corrected for diaphragm.	Ratio $\frac{VIII}{VI}$ proportional to transmission of spectrometer.	Wave-length.
		Usual position.			Position at slit.				
		Deflection A.	Diaphragm.	Time (p. m.).	Deflection B.	Time (p. m.).			
		mm.		*h. m.*	*mm.*	*h. m.*			*μ*
483.0	186.5	8.0	0	1 33	3.3	1 45	9.3	2.82	0.391
462.0	188.0	33.8	0	1 32	9.5	1 45	39.2	4.13	0.406
441.7	189.5	54.0	0	1 31	14.0	1 46	62.6	4.47	0.422
414.9	191.5	115.1	0	1 29	25.5	1 47	133	5.22	0.449
387.3	193.5	67.2	1	1 28	44.0	....	254	5.77	0.485
354.0	196.0	49.8	2	1 27	77.0	1 48	498	6.47	0.548
327.2	198.0	75.8	2	1 25	113.5	....	758	6.68	0.629
295.0	200.4	129.9	2	1 23	187.0	....	1,299	6.95	0.800
270.9	202.2	156.6	2	1 21	217.0	1 50	1,566	7.22	1.045
260.1	203.0	138.8	2	1 20	195.0	....	1,388	7.12	1.216
239.8	204.5	80.8	2	1 18	116.0	....	808	6.97	1.640
215.2	206.3	123.7	0	1 17	30.0	1 52	143	4.77	2.125

TABLE 5.—*Computation of reflecting power of cœlostat (two silvered mirrors).*

One-tenth of prismatic deviation from F line.	Wave-length.	Measured ordinates of bolographs.					Reflecting[2] power of cœlostat $\frac{B}{\left(\frac{A+C}{C+E}\right)D}$	First[3] determination.	Mean.
		A [8][1]	B [9]	C [10]	D [11]	E [12]			
′	μ								
−14	(0.390)	180	135	190	220	205	.658	.704	.681
−12	0.400	450	318	457	480	440	.654	.685	.669
−10	0.411	650	478	623	680	660	.719	.671	.695
− 8	0.424	773	625	784	860	810	.752	.709	.730
− 6	0.436	1,050	820	1,028	1,128	1,108	.758	.758	.758
− 4	0.451	1,495	1,220	1,480	1,570	1,557	.800	.763	.781
− 2	0.468	585	510	625	670	625	.781	.847	.814
0	0.488	742	640	747	823	775	.800	.855	.827
+ 2	0.510	912	792	910	988	930	.813	.847	.830
+ 4	0.537	1,139	986	1,137	1,225	1,157	.813	.862	.837
+ 6	0.569	1,370	1,207	1,378	1,530	1,402	.800	.870	.835
+ 8	0.611	663	600	667	747	670	.813	.847	.830
+10	0.664	820	770	810	915	813	.847	.847	.847
+12	0.732	1,010	978	979	1,110	1,020	.893	.893	.893
+14	0.826	1,200	1,152	1,142	1,280	1,210	.917	.901	.909
+16	0.954	1,295	1,260	1,240	1,395	1,320	.926	.917	.921
+18	1.131	1,222	1,193	1,160	1,317	1,240	.926	.952	.939
+20	1.392	960	933	915	1,030	980	.926	.926	.926
+22	1.686	625	610	610	700	650	.901	1.000	.950
+25	2.082	1,280	1,280	1,230	1,380	1,300	.943	.943	.943

[1] See numbers of bolographs, Table 3.
[2] In the actual interpolation allowance is made for the exact air masses at the times of observation, but the expression given above indicates substantially the method.
[3] Another independent determination of the reflecting power was made earlier on the same day, and the mean of both results was used in further reductions.

Table 6.—*Pyrheliometer readings.*

[Secondary pyrheliometer, No. IV. Readings each 20 seconds. Alternately shade and sun exposure for 2-minute intervals.]

Apparent solar time.	Reading.	Reduction.[1]	Apparent solar time.	Reading.	Reduction.[1]	Apparent solar time.	Reading.	Reduction.[1]
a. m.	°		*a. m.*	°		*a. m.*	°	
6^h41^m	18. 32		7^h01^m	22. 96		7^h29^m	28. 60	——
	. 34			23. 51			. 54	1. 641
	. 36			. 99			. 47	1. 480 cal.
	. 39			24. 47			. 41	
	. 42			. 94			. 36	
	. 44			25. 40	1. 569		. 31	
					−13			
6^h43^m	18. 92		7^h03^m	25. 44	——	7^h31^m	28. 75	
	19. 43			. 36	1. 556		29. 24	
	. 96			. 30	1. 404 cal.		. 72	
	20. 48			. 24			30. 18	
	. 96			. 18			. 63	
	21. 42	1. 515		. 14			31. 06	
		−20						
6^h45^m	21. 42	——	7^h05^m	25. 49		7^h33^m	31. 00	1. 641
	. 38	1. 495		. 96			30. 87	1. 480 cal.
	. 35	1. 348 cal.		26. 42			. 75	
	. 32			. 86			. 65	
	. 29			27. 29			. 54	
	. 25			. 72			. 44	
					1. 587			
6^h47^m	21. 61		7^h07^m	27. 70	−8	8^h12^m	27. 24	
	22. 09			. 58	——		. 24	
	. 55			. 48	1. 579		. 24	
	23. 00			. 36	1. 424 cal.		. 24	
	. 44			. 26			. 23	
	. 86	1. 518		. 17			. 23	
		−14						
6^h49^m	23. 84	——	7^h25^m	25. 54		8^h14^m	27. 75	
	. 75	1. 504		. 54			28. 33	
	. 67	1. 357 cal.		. 54			. 86	
	. 60			. 54			29. 40	
	. 53			. 54			. 92	
	. 45			. 54			30. 44	1. 731
								−2
6^h59^m	22. 60		7^h27^m	26. 01		8^h16^m	30. 40	——
	. 59			. 58			. 32	1. 729
	. 57			27. 10			. 24	1. 560 cal.
	. 56			. 61			. 16	
	. 55			28. 12			09	
	. 55			. 61	1. 647		. 02	
					−6			

[1] In the column marked "Reduction" there is given the mean rise of temperature per minute corrected for cooling, a small correction depending on the temperature of the instrument, and the number of calories per square centimeter per minute corresponding to the corrected rise of temperature.

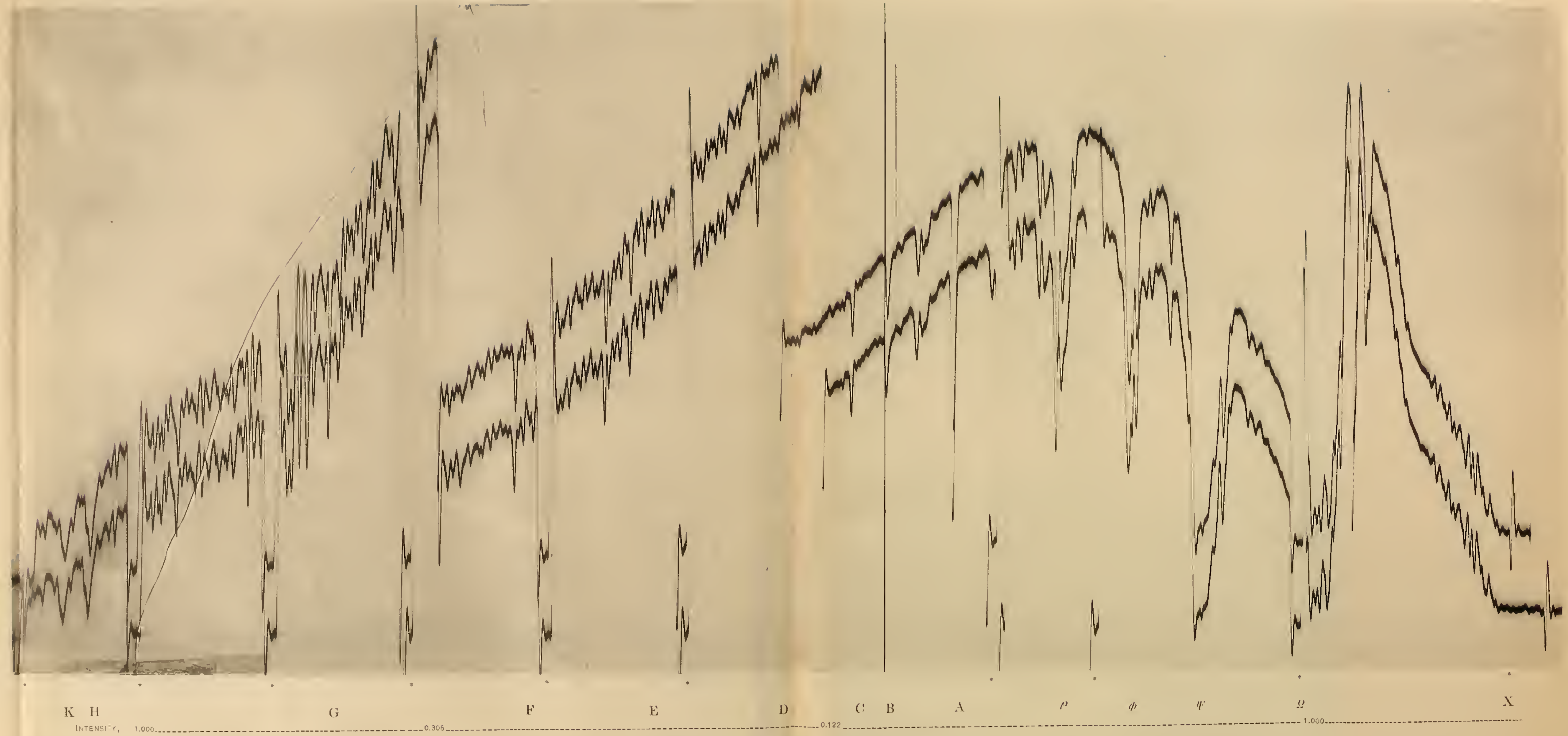
15000—08——5

TABLE 6.—*Pyrheliometer readings*—Continued.

Apparent solar time.	Reading.	Reduction.
a. m.	°	
8^h18^m	30.49	
	31.00	
	.47	
	.94	
	32.40	
	.85	1.719
		+5
8^h20^m	32.75	
	.62	1.724
	.50	1.555 cal.
	.37	
	.24	
	.12	
8^h38^m	29.81	
	.81	
	.80	
	.80	
	.80	
	.80	
8^h40^m	30.37	
	.94	
	31.51	
	32.04	
	.57	
	33.07	
8^h42^m	33.04	1.737
	32.96	+5
	.87	
	.80	1.742
	.74	1.571 cal.
	.66	
8^h44^m	33.13	
	.64	
	34.14	
	.60	
	35.07	
	.52	1.737
		+9
8^h46^m	35.42	
	.29	1.746
	.15	1.575 cal.
	.03	
	34.91	
	.79	

Apparent solar time.	Reading.	Reduction.
a. m.	°	
9^h10^m	32.52	
	.53	
	.54	
	.55	
	.56	
	.56	
9^h12^m	33.08	
	.67	
	34.24	
	.80	
	35.34	
	.87	1.749
		+9
9^h14^m	35.84	
	.77	1.758
	.70	1.586 cal.
	.64	
	.57	
	.51	
9^h16^m	35.99	
	36.52	
	37.03	
	.51	
	38.00	
	.44	1.752
		+16
9^h18^m	38.35	
	.22	1.768
	.08	1.595 cal.
	37.95	
	.84	
	.74	
9^h38^m	35.31	
	.31	
	.31	
	.30	
	.30	
	.30	
9^h40^m	35.84	
	36.43	
	.97	
	37.52	
	38.05	
	.56	1.752
9^h42^m	38.53	+15

Apparent solar time.	Reading.	Reduction.
a. m.	°	
	.44	1.767
	.36	1.594 cal.
	.29	
	.21	
	.14	
9^h44^m	38.58	
	39.09	
	.59	
	40.07	
	.54	
	41.01	1.770
		+23
9^h46^m	40.88	
	.75	1.793
	.61	1.617 cal.
	.48	
	.35	
	.23	
10^h33^m	37.54	
	.54	
	.55	
	.56	
	.57	
	.59	
10^h35^m	38.07	
	.67	
	39.26	
	.83	
	40.39	
	.91	1.803
		+22
10^h37^m	40.94	
	.86	1.825
	.78	1.646 cal.
	.70	
	.64	
	.56	
10^h39^m	40.96	
	41.50	
	42.00	
	.47	
	.95	
	43.40	1.794
		+30
10^h41^m	43.38	



BOLOGRAPHS OF SOLAR SPECTRUM OF 60° GLASS PRISM.

* Shutter Interposed to Indicate Zero of Ordinates

TABLE 6.—*Pyrheliometer readings*—Continued.

Apparent solar time.	Reading.	Reduction.	Apparent solar time.	Reading.	Reduction.	Apparent solar time.	Reading.	Reduction.
a. m.	°		*a. m.*	°		*a. m.*	°	
	.23	1.824	12^h09^m	40.61		12^h13^m	42.98	
	.08	1.645 cal.		41.15			43.46	
	42.94			.68			.92	
	.80			42.21			44.36	
	.66			.72			.79	
				43.19	1.797		45.20	1.794
12^h07^m	40.36				+29			+32
	.33		12^h11^m	43.32		12^h15^m	45.12	
	.30			.17	1.826		44.94	1.826
	.25			.05	1.647 cal.		.75	1.647 cal.
	.21			42.93			.55	
	.17			.80			.37	
				.68			.22	

REDUCTION OF SPECTROBOLOMETRIC OBSERVATIONS OF AUGUST 8, 1906, BY F. E. F., F. A. G., C. V. B., AND J. C. D.

In preparation for reduction, smoothed curves were drawn with ink on each plate so as to give the average height of each curve; that is to say, these ink lines passed through a mean position between crest and trough of all depressions corresponding to the solar absorption lines excepting K, H, and a few others, and were drawn smoothly over the tops of terrestrial absorption lines like A, $\rho\sigma\tau$, φ, ψ, and Ω. The ordinates of these ink lines were then measured at 44 points situated 1 centimeter apart in abscissæ on the bolographs. For all bands of large terrestrial and solar selective absorption the area between the smoothed curves and the bolographic curves was measured. The ordinates and the areas of bands were next corrected for effective height of slit and absorption of cœlostat and spectrometer by the aid of factors determined from the observations above given. Next from the sum of corrected ordinates was subtracted the sum of the corrected band areas. Inasmuch as the bolograph, as corrected, represents the distribution of radiation in the solar spectrum at the surface of the earth, the sum of its ordinates at numerous points situated at equal intervals apart is substantially proportional to the total radiation. Accordingly the difference just obtained represents the total energy of the spectrum as observed by the bolometer. A small correction, determined in part by extrapolation and in part by knowledge of the solar spectrum at long wave-lengths, was added to represent the radiation of small and great wave-lengths outside of the region of spectrum observed by the bolometer, but affecting the pyrheliometer. The corrected result was next compared with the pyrheliometer readings representing the total radiation of the sun, corresponding to the time of passing the "C" line on the bolographs, which was chosen as best representing the time of observation. From this comparison was determined a mean constant multiplier for reducing the summation of intensities to actual calories, and also a series of correcting factors to allow for change of sensitiveness of the bolometric apparatus during the day's observations. Each corrected ordinate was then further multiplied by the correcting factor appropriate to the bolograph to which it belonged. At this stage the logarithms of the corrected ordinates were plotted as ordinates, and the secant of the sun's zenith distance (or air mass) at corresponding times as abscissæ. From the 44 plots thus prepared the best representative straight lines were produced to intersect the axis of ordinates at zero air mass. At this point the ordinate of intersection was read off, which corresponded to the logarithm of intensity of solar radiation outside the atmosphere for the given wave-length. Summing up the numbers corresponding to these extrapolated points, a result was obtained which was regarded as proportional to the total solar intensity of radiation outside our atmosphere within the range of wave-lengths covered by the bolographs. To this sum was added 0.013 of itself as an allowance for the solar energy of less wave-length than the smallest observed, and 0.0055 of itself for that of greater wave-length than the greatest observed.[1] The corrected sum was then multiplied by the constant above mentioned, as obtained from the comparison of bolographs with pyrheliometer readings, in order to express the solar radiation in calories, and to the product was added 0.029 of itself to reduce the result to mean solar distance.

It is unnecessary to publish the entire computation just described, but a summary including the details of measurement and reduction for one wave-length, and illustrated by logarithmic plots (see Pl. XIV) corresponding to six different wave-lengths, is given to fix ideas.

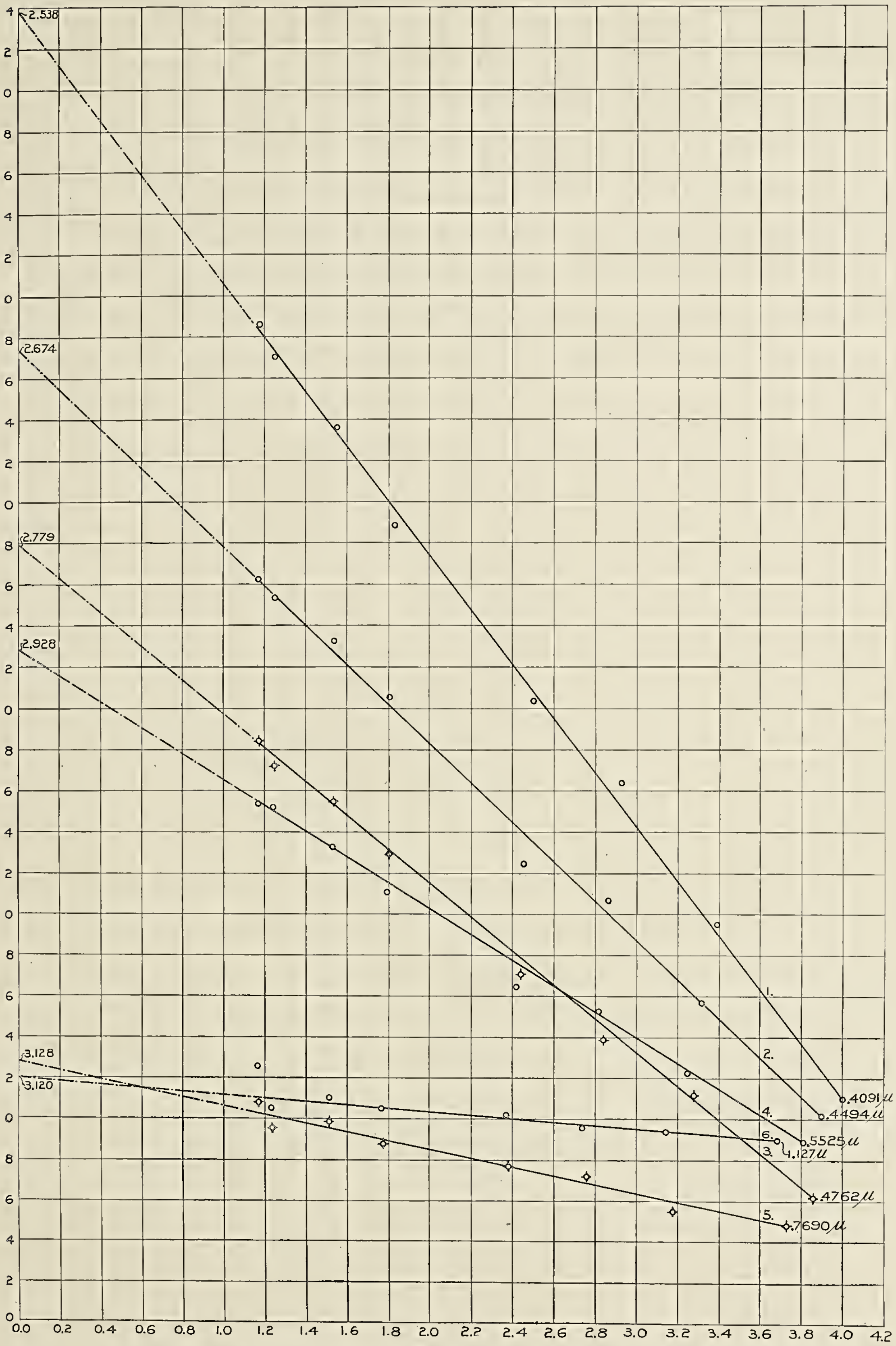
TABLE 7.—*Measurements and reduction at wave-length 0.537μ.*

[August 8, 1906.]

Bolograph number	1	2	3	4	6	8	10	12
Measures	970	987	1, 039	1, 107	1, 200	1, 139	1, 137	1, 157
Corrected for slit aperture	391	398	419	446	484	459	458	466
Corrected for absorption of apparatus	770	784	825	878	953	904	903	919
Corrected for change of sensitiveness of spectrobolometer	743	769	809	883	908	927	959	940
Air mass=Secant Z	2. 935	2. 630	2. 314	1. 672	1. 425	1. 271	1. 172	1. 110
Logarithm of corrected measure	871	886	908	946	958	967	982	973

Logarithm of coefficient of atmospheric transmission	—(0. 058)
Logarithm of intensity at zero air mass	3. 043
Transmission coefficient	0. 875
Intensity at zero air mass	1. 104

[1] These allowances were determined by consideration of the form of the energy spectrum of the "black body" at 6,000° absolute temperature.



LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION, MOUNT WILSON, AUGUST 25, 1906.

TABLE 8.—*Summary of determination of "solar constant" by bolometry and pyrheliometry combined.*

[August 8, 1906.]

Bolograph number	1	2	3	4	6	8	10	12
First trial sum	35, 405	35, 608	36, 342	37, 567	40, 192	37, 586	36, 906	38, 422
Area of bands	3, 666	3, 545	3, 337	3, 230	3, 371	2, 971	3, 053	2, 904
Difference	31, 739	32, 063	33, 005	34, 337	36, 821	34, 615	33, 853	35, 518
Pyrheliometer observations reduced to calories	1. 382	1. 420	1. 463	1. 555	1. 579	1. 600	1. 628	1. 647
Ratio (mean, 451)	435	443	443	453	429	462	481	464
Correcting factor for sensitiveness of spectrobolometer	. 9645	. 9823	. 9823	1. 004	. 9512	1. 024	1. 067	1. 029

Sum of ordinates at zero air mass, 47,591.
Correction for ultra violet, 619.
Correction for infra red, 262.
Sum total, 48,472.
Radiation in calories, 1.972.
Same corrected to mean solar distance, 2.029.
Grade of day's work "Excellent," number of logarithmic plots marked "Excellent" being 32 of possible 44.

EXTRAPOLATION BY MEANS OF PYRHELIOMETRY ALONE (MINIMUM VALUE OF THE "SOLAR CONSTANT").

Plotting logarithms of pyrheliometer observations as ordinates, and air masses at corresponding times as abscissæ, and producing the most representative straight line to intersect the axis of ordinates at zero air mass, the number of calories corresponding was found to be 1.827. Adding 0.029 of itself to reduce to mean solar distance, we obtain 1.880 calories. This number, as previously explained, is necessarily less than the "solar constant" because of the different transmission of different solar rays in the earth's atmosphere. The difference between it and 2.029 calories found by the method of homogeneous rays is due to the impossibility of estimating atmospheric transmission correctly by the pyrheliometer alone. The average apparent transmission of the atmosphere above Mount Wilson for all wave-lengths as derived from pyrheliometry of August 8, 1906, was 0.908. As previously explained, this exceeds the real average transmission.

Chapter IV.

INVESTIGATION OF SOURCES OF ERROR IN THE DETERMINATION OF THE "SOLAR CONSTANT."

The determination of the "solar constant" by the method of high and low sun described in detail in preceding chapters requires the measurement of the intensity of solar radiation at the surface of the earth for all wave-lengths and for different zenith distances of the sun. In our practice this is accomplished by the use of the recording spectrobolometer, an instrument adapted to give relative measurements of radiation by automatically recording the relative rise of temperatures caused in a blackened platinum strip when exposed successively to the radiations in question. Admitting for the moment the accuracy of this record for relative measurements, and that proper allowance is made for the imperfect transmission of the rays to the bolometer, the interpretation of the record requires a comparison of the bolometric indications with those of an instrument furnishing absolute measurements of radiation, which is in our practice the standard pyrheliometer. It is found convenient to make this comparison indirectly through a secondary pyrheliometer. Thus, to insure correct estimation of the solar radiation at the earth's surface, it is necessary to investigate the errors which may arise in the use of the standard pyrheliometer, the secondary pyrheliometer, and the optical and electrical parts of the spectrobolometer. But more doubtful and insidious sources of error are thought by many to lurk in the theoretical procedure by means of which the loss of radiation which the solar beam suffers in its passage through the atmosphere is estimated. It is to this latter class of difficulties that we first turn our attention.

ERRORS OF EXTRAPOLATION.

1. TRANSMISSION OF MONOCHROMATIC RAYS THROUGH A HOMOGENEOUSLY MIXED MEDIUM.

It is assumed that when a monochromatic ray traverses a medium composed of gases and dust particles forming a *uniform mixture*, equal thicknesses of the medium transmit equal fractions of the light reaching them, independently of the thickness of medium which the light has previously traversed.

This principle appears not to have received adequate experimental verification, though universally accepted as sound. It would obviously be liable to error in case the transmission coefficient depends on the intensity of the incident light. The strongest evidence that the transmission of the earth's atmosphere is independent of the intensity of the light traversing it is found in the fact that approximately equal transmission coefficients have been found by different observers for starlight and sunlight. This evidence is not sufficient for rigid proof, because the earth's atmosphere taken as a whole is far from being a uniform mixture, and the observations of starlight have not been made with monochromatic rays. But taking into consideration the fact that sunlight has millions of times the intensity of starlight and that the coefficients of transmission found for the two by photometric processes vary only a few per cent, there seems to be no reasonable ground to suspect that the transmission depends upon the intensity.

2. LAMELLAR STRUCTURE OF THE EARTH'S ATMOSPHERE.

It is assumed that within the narrow region affecting "solar-constant" observations the earth's atmosphere may be regarded as composed of concentric shells, each of which is a homogeneously mixed medium remaining for several hours of uniform transmissibility throughout, but differing slightly from neighboring shells in transmissibility.

This requirement is of course only approximately fulfilled, at best, and is so widely departed from at all times in some localities, and occasionally even in the best localities, that "solar-constant" work in unfavorable conditions is useless.

Let us consider first the variations which occur in the permanently gaseous atmosphere. Barometric pressure diminishes so regularly with increasing altitude that the elevations of mountains and balloons are often determined by barometric observations. Nevertheless, the surfaces of equal mean barometric pressure are not strictly concentric with the earth, but depend on several variables, notably on the temperature of the air. According to Ferrel the mean barometric pressure for various latitudes and levels is as follows:[1]

Mean barometric pressure, northern hemisphere.

Latitude	0°	10°	20°	30°	40°	50°	60°	70°	80°
Sea-level	758.0	757.9	759.2	761.7	762.0	760.7	758.7	758.6	760.5
2 kilometers	601.1	600.9	600.9	600.9	598.0	593.0	587.6	583.6	582.0
4 kilometers	471.0	470.7	469.9	468.3	463.6	457.0	451.9	446.6	445.2

Supan[1] computes for a height of 8,000 meters a gradual decrease of air pressure amounting to 50 mm. (corresponding to 1,360 meters change of level of the surface

[1] See Hann's Lehrbuch der Meteorologie, pp. 469, 470.

of equal pressure) between the latitudes 0° and 80° north, and as between the Atlantic Ocean and Eastern Siberia at 60° north latitude he gives the following computed values:

Mean barometric pressure at 60° north latitude—January.

Height in kilometers	0	2	4	6	8
Atlantic Ocean	744	576	441	334	251
East Siberia	778	584	439	326	240

From these figures it is obvious that the surfaces of equal altitude are by no means the surfaces of equal barometric pressure taking the whole world over.

Fortunately this is not required for "solar-constant" observations. All the air with which we are concerned is included in the triangular figure swept over by the slender cone joining the observing station with the sun, during a time not necessarily exceeding three hours. It will serve to show how limited are the shells of equal transparency, whose situation is required to be concentric with the earth, if we determine the cross section of the circular cylinders whose axes lie in the line joining the observer with the zenith, and whose surfaces entirely inclose the beam of light in question, in its path at 70° zenith distance, below certain atmospheric levels.

Areas of cross section of cylinders inclosing beam of 70° zenith distance.

Below level given in kilometers	10	25	50	100
Area of cross section of cylinder in square kilometers.	2, 400	15, 000	60, 000	240, 000
Fraction of entire surface of the earth	0. 000005	0. 00003	0. 0001	0. 0005

Substantially all the absorbing atmosphere is included below the 25 kilometer level, so that the gradual variations of mean barometric pressure over the earth's surface evidently have no significance as affecting the concentric distribution of barometric pressure over the relatively insignificant area here in question.

The daily variation of the barometer at a given locality comes next in consideration.[1] This is a maximum at the equator, and diminishes with both increasing latitude and increasing altitude. At sea-level, on the equator, variations of 2 to 3 mm. are usual, while between latitudes 33° and 43° variations of 1 mm. would be normal. The change during daylight hours is generally most rapid from 5 to 8 o'clock a. m., and from 11 a. m. to 2 p. m., but there are many exceptions to this, and to the preceding general rules. But the change to be expected during any single period of "solar-constant" observation, either at Washington or Mount Wilson, does not much exceed one-thousandth part of the total pressure of air, and is negligible for the present work.

[1] See Hann's Lehrbuch der Meteorologie, pp. 177–184.

So far then as concerns the uniformity of the concentric distribution of the permanently gaseous atmospheric layers, as indicated by the air pressure, there is no reason to believe that hurtful departures need be feared under ordinarily good conditions.

But the atmosphere is charged with water vapor, clouds, dust, and haze, all of which are more variable in their distribution than the permanent gases. As these substances are most plentiful near the sea-level, and in the vicinity of railroads and cities, it is clearly of advantage to conduct "solar-constant" observations at retired high level stations. Still there is reason to think that occasionally there occur cloudless days when the strata of haze, dust, and water vapor remain sufficiently undisturbed for several hours in succession, to render it possible to obtain good results at sea-level stations like Washington. Further evidence on this point will be presented later.

From Mount Wilson the observer usually sees an apparently dense layer of haze and dust, lying in the forenoon well below him, but often rising above the top of the mountain during the afternoon. On a great many days a cloud of fog whose upper surface is from 500 to 1,500 meters above sea-level, hides the valley and ocean completely from view during the early morning hours, but breaks up at 9 or 10 o'clock a. m. The haze, fog, and dust all lie usually in layers so level and smooth that deviations in level of 100 meters would seem to be the exception and not the rule. The view of these strata can not but tend to inspire confidence in the substantially accurate concentric distribution of these variable elements; and the sight of their upper surfaces projected against the sides of mountains lower than Mount Wilson, inspires added faith in the uniformity of the air above. Observations of this kind lead to the belief that the forenoon is generally the better time for "solar-constant" work on Mount Wilson, and this is confirmed by the reduction of the measurements. Still it is satisfactory also to find that the final results of forenoon and afternoon observation on the same day generally agree within 1 per cent, although the transmission of the sky may be considerably different in the two parts of the day.

The following table shows the change in the pressure of water vapor during a good day on Mount Wilson, as determined by careful observations in the shade with the sling psychrometer:

Observations with sling psychrometer, August 8, 1906—Mount Wilson.[1]

[Observer, L. R. I. Barometer 24.7 inches.]

Time	7^h20^m a. m.	8^h23^m a. m.	8^h50^m a. m.	9^h20^m a. m.	9^h48^m a. m.	10^h27^m a. m.	0^h15^m p. m.	1^h10^m p. m.	2^h0^m p. m.	6^h20^m p. m.
Wet bulb	48°.7 F.	49°.5 F.	50°.5 F.	52°.8 F.	51°.9 F.	52°.8 F.	57°.0 F.	55°.8 F.	55°.5 F.	48°.4 F.
Dry bulb	69°.0 F.	69°.5 F.	70°.9 F.	73°.8 F.	72°.9 F.	73°.4 F.	75°.0 F.	74°.0 F.	74°.0 F.	68°.2 F.
Pressure of vapor in millimeters	4.01	4.34	4.60	5.28	4.95	5.38	7.64	7.09	6.91	4.04

[1] See details of bolometric work of this day given in Chapter III.

On this day bolometric observations for the determination of the "solar constant" continued from 6^h 45^m a. m. to 10^h 40^m a. m., during which time the pressure of water vapor increased from 4.0 mm. to 5.4 mm. Undoubtedly this would produce some effect in certain regions of the spectrum, but this is mainly allowed for by the device of eliminating the water vapor bands wholly, by smoothing the bolographic curves in the regions of great water vapor absorption. The tendency of the error introduced in forenoon observations at Mount Wilson by the increase of water vapor probably is to yield slightly too small values of the "solar constant." It is probable that the great increase of the pressure of vapor about noon (a phenomenon almost always observed) is caused by the rise of a sea breeze. The subsequent decrease of pressure unfortunately tends to produce error in afternoon determinations affecting the "solar constant" in the same direction as in the forenoon; but the rate of change of vapor pressure is so much greater in the afternoon that if the error was considerable it would appear by causing the afternoon values to fall below those of the morning, but in fact there seems to be little difference between forenoon and afternoon determinations, as shown by the following table, and the differences observed lie oftener in the other direction.

"Solar constant" determinations—Mount Wilson, 1905.

Date	July 25	Aug. 11	Aug. 25	Aug. 30	Sept. 8	Oct. 18
Forenoon determination	2.05	2.034	2.05	1.93	2.03	2.01
Afternoon determination	2.05	2.058	2.08	1.96	2.00	2.03

As the general result of all the preceding discussion, it seems probable that above Mount Wilson generally, and above Washington occasionally, the shells of equal optical transparency are sufficiently horizontal and constant in their arrangement for good determinations of the "solar constant" by the method of high and low sun observations.

3. THE HEIGHT OF THE ABSORBING ATMOSPHERE.

It is assumed that the atmosphere exercises no appreciable effect on the transmission of the solar beam above an altitude of 100 kilometers.

Laplace concluded that the earth carries with it a volume of gas extending to a distance of about six and a half radii from the earth's center, but the density of this gas is so excessively small that no certain evidences of it can be obtained either from twilight observations, auroræ, meteors, or lunar eclipses beyond the height of 300 kilometers from the surface of the earth. At this height Hann gives the probable barometric pressure at 35×10^{-17} millimeters of mercury, which is so far beyond our experience of a vacuum that it seems out of the question to conceive of atmospheric absorption of consequence at this height. The probable barometric pressure at 100 kilometers is given by Hann at about 0.003 millimeter of mercury, or less than 0.00003 the difference of pressure between Washington and Mount Wilson. If the air above 100 kilometers in altitude instead of being absolutely pure and dustless were as gross as that of the lower layers of atmosphere, it would therefore produce less than 0.000015 calorie difference in the amount of sunlight reaching us, which for our purpose is a quantity wholly inappreciable.[1]

4. AIR MASS.

It is assumed that the length of path of the solar beam in each of the homogeneous shells mentioned under caption 2 is equal to the thickness of the shell multiplied by the secant of the apparent zenith distance of the sun.

This assumption holds with sufficient approximation for small zenith distances, and it interests us here to inquire to how great zenith distances we may apply it without falling into appreciable error. The curvature of the shells tends to diminish the length of path in the outer ones, while the atmospheric refraction tends to increase it; but for zenith distances less than 70° the effect of refraction is negligible compared with that of curvature.

Let z be the apparent zenith distance of the source of light, r the radius of the earth, x the distance of a certain shell of atmosphere above the earth's surface, and α the decrease in zenith distance of the source as viewed from the outside of the said shell, due to the curvature of the earth, then

$$\sin \alpha = \frac{1}{2}\left\{\sqrt{1 + \frac{2x}{r}\tan^2 z + \frac{x}{r}} - 1\right\} \sin 2z \text{ approximately.}$$

By the aid of this formula the following table has been prepared:

TABLE 9.—*Correction to length of path of beam on account of curvature of air shells.*

Height of shell.	10 km.	25 km.	50 km.	100 km.	Secant.
Apparent zenith distance z.	Ratio of path within shell to secant z.				z.
60°	0.996	0.993	0.982	0.957	2.000
65°	.992	.981	.964	.934	2.366
70°	.988	.972	.946	.902	2.924

As appears from the table, there is a very considerable change in the length of path of the beam in the several layers of the air, even at 60° zenith distance, so that if the air were of equal density from the surface of the earth up to 100 kilometers height the total air mass would depart notably from secant z even at 60° zenith distance; but it must be remembered that the density of the upper air is so small and its purity so high that it exercises very little absorption on the

[1] The effect of the centrifugal force due to the earth's rotation is quite too small to influence this result sensibly.

beam. In Hann's "Lehrbuch der Meteorologie," page 9, the pressure of the air at various heights is estimated as follows:[1]

Height	$0^{km.}$	$10^{km.}$	$20^{km.}$	$50^{km.}$	$100^{km.}$
Pressure	$760^{mm.}$	218.1	18.26	1.55	0.00344

If we combine the different layers of air in proportion to their actual density to make up the total air mass, undue influence will be given to the higher layers, because they are really of greater optical purity; hence the following table, made up from the figures already given, gives an exaggerated value of the error of the secant formula, because no allowance is made for the less transparency of the lower layers:

TABLE 10.—*Error of secant formula for total air mass.*

Height.	Correction factor for curvature of shell at mean height for zenith distance.			Fraction of atmosphere included.	Product of correction factor by fraction of weight of total atmosphere at zenith distance.		
km.	60°	65°	70°		60°	65°	70°
0 to 10	0.998	0.996	0.994	0.713	0.7115	0.7101	0.7087
10 to 25	.995	.986	.980	.269	.2677	.2652	.2636
25 to 50	.988	.972	.959	.016	.0158	.0156	.0153
50 to 100	.970	.949	.924	.002	.0020	.0019	.0018
Sums					.9970	.9928	.9894

It thus appears that when the errors of air mass due to the curvature of the several shells are considered in connection with the relative weights of air affected by them the errors of total air mass at 60°, 65°, and 70° zenith distance come out at 0.0030, 0.0072, and 0.0106, respectively.

Small as these values are, they overstate the errors in question, for the slight compensating effect of refraction is neglected. The correction factors for curvature used are those applicable at heights of 5 km., 17.5 km., 37.5 km., and 75 km., whereas on account of the variation of density by geometrical progression the factors corresponding to somewhat lower layers should be used, and, finally, the optical density of the lowest layers is disproportionately greater than that of the higher ones, so that the lower layers ought to receive greater weight than is here accorded to them.

Accordingly, we may conclude that there will be no error of air mass above 1 per cent in magnitude introduced if we employ the simple secant formula up to zenith, a distance of 70°, which corresponds to air mass 3.0, and beyond this there is no need to go.

5. MONOCHROMATIC RAYS.

It is assumed that in the bolographic records the distribution of the energy of the spectrum is represented with sufficient detail to permit of the determination of an adequate number of atmospheric transmission coefficients.

[1] The variation of centrifugal force with the altitude is of no consequence for the present purpose.

As first shown by Langley, and stated on an earlier page of this volume, the total intensity of a beam of light outside the atmosphere can not be estimated from observations of its intensity after transmission through different thicknesses of air if the beam is separable into parts of unequal transmissibility. Thus, if the observations of the pyrheliometer alone are treated by the same method as the spectrobolometric measures to determine the "solar constant," the pyrheliometer determinations fall from 8 to 14 per cent lower than the others, because the transmission of the different rays composing solar radiation is unequal. But how are we assured that the bolometer discriminates all the regions of selective absorption? It is conceivable, for instance, that what is termed loosely the general absorption of the air, which apparently increases gradually from the red to the violet, may in reality be the apparent effect of what is really a series of innumerable and undiscoverable bands of alternately great and small absorption. If this is truly the case, there is no dependence to be placed on "solar-constant" determinations. But this possibility is exceedingly unlikely, for two reasons—first, the emission spectrum of air in vacuum tubes has no continuous or discontinuous spectrum covering the whole range of wave-lengths through which the general absorption extends and only shows the comparatively infrequent lines of the gases of the atmosphere; second, Lord Rayleigh has explained the apparent absorption of the atmosphere as a perfectly continuous function of the wave-length, and his theory agrees quantitatively with the observed facts.

We may then dismiss the possibility that the apparent general absorption of the air is caused by alternate fine lines of great and small selective absorption, and admit only the selective influence of the known bands of the atmospheric gases and vapors. Of these the great bands of oxygen and water vapor are eliminated from effect by the device of smoothing the bolographic curves, as explained in Chapter III. As for the narrower terrestrial bands and lines, their effect may be estimated by measuring the width of each of the atmospheric lines shown in Rowland's solar-spectrum map not included in the bands α, B, and A, and comparing the sum of all their widths with the width of the whole spectrum photographed by him. The numbers will show that even if the absorption in these lines was total, so that no allowance was made for them in ordinary extrapolation, the whole error caused by their neglect would be entirely negligible.

NUMBER OF TRANSMISSION COEFFICIENTS NECESSARY TO BE DETERMINED.

In theory the number of points in the spectrum where transmission coefficients ought to be determined, should be the same as the number of rays whose transmission differs from that of their neighbors. But it is not practicable to go

[1] London, Edinburgh, and Dublin Philosophical Magazine, series 4, vol. 41, p. 107, 1871; also, series 5, vol. 47, p. 377, 1899.

to this length in reduction, and practically the measurements have been limited to 44 places in the spectrum. This number of places seems to be fully adequate, because it has been found by actual trial that "solar-constant" values not differing by more than 1 per cent are reached when only half as many transmission coefficients are used in one computation and the full number in another. But for the reason that accidental errors sometimes detract from the accuracy of some of the transmission coefficients, it is found best to employ the larger number of points in the definitive reductions.

This completes the discussion of the theory of the errors of extrapolation in "solar-constant" determination; but before passing on to the treatment of instrumental errors it may be remarked that support to the belief in the soundness of the method which the discussion tends to confirm is found in the fact that the plots (like those shown in Pl. XIV) whose ordinates are logarithms of heights of the bolographs and whose abscissæ are secants of the solar zenith distance, show no departures from straight lines other than those plainly attributable to accidental errors. This is illustrated by the following table, which gives the actually measured ordinates (*d*) as corrected to normal sensitiveness of the bolometer, and the departures (δd) of the ordinates of bolographs from those which would yield the best straight lines for a number of wave-lengths, as determined from the bolographs taken on Mount Wilson September 20, 1906—an excellent day, but not better than a large number of others. The values of secant z are mean values for each bolograph and are given only approximately.

TABLE 11.—*Departures of secant formula from bolographic observations.*

Wave-length (μ).		0.4037		0.4417		0.4861		0.5697		0.7280		1.127		2.060	
Bolograph.	Secant z.	d.	δd.	d.	δd.	d.	δd.	d.	dδ.	d.	δd.	d.	δd.	d.	δd.
		mm.	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*	*mm.*
1...........	5.0-4.3	8.4	+0.14	30.8	−1.14	26.5	−0.24	66.3	−0.38	71.3	+0.07	100.2	+0.08	100.2	+0.49
2...........	3.7-3.3	13.3	−0.38	40.2	+0.04	33.1	±0.00	76.6	+0.41	76.6	−0.07	102.7	−0.50	106.5	+0.74
3...........	2.80	15.6	+0.64	47.2	−0.55	37.3	+0.35	84.6	+0.24	79.7	−0.07	105.8	+0.33	108.2	−0.54
4...........	2.00	21.5	−0.04	59.4	+0.96	43.4	+0.40	95.9	−0.72	84.0	−0.49	108.0	+0.17	113.0	−0.56
5...........	1.70	23.7	−0.10	62.6	−0.37	46.7	−0.32	99.9	−0.63	85.1	±0.00	109.0	−0.25	116.0	−0.97
6...........	1.48	25.3	+0.11	68.2	+1.77	49.0	−0.78	102.1	−0.35	85.3	+0.98	109.2	+0.16	114.4	+2.18
7...........	1.33	26.8	−0.07	69.0	±0.00	49.8	−0.12	104.5	+0.18	87.7	−0.64	110.0	−0.10	118.3	−0.92
8...........	1.23	27.2	+0.43	67.7	−2.98	49.0	+1.71	104.0	+1.71	86.8	+0.70	109.3	+3.50	117.1	+0.64
Mean...	....	......	0.24	......	0.98	......	0.49	....	0.58	......	0.38	....	0.64	....	0.88

It appears from the table that the measured values of *d* fit the logarithmic straight-line plots very closely, and there seems to be no tendency to greater departures for any particular air masses. When the great complexity of the bolometric apparatus is considered, and also the close degree of uniformity of the transparency of the sky which this result indicates is taken into the account, it seems remarkable that the departures are so small.

ERRORS OF OBSERVATION.

The errors of observation fall naturally in two groups: First, the errors in determining the total solar radiation at the earth's surface; second, the errors in determining the distribution of solar radiation in the spectrum, and the effect of the absorption of the atmosphere and the apparatus thereon. The first of these two kinds of errors pertains to the pyrheliometers, the other to the spectrobolometer.

1. ERRORS OF PYRHELIOMETRY.

The "solar-constant" work of the Astrophysical Observatory depended entirely for several years on the constancy of a scale of pyrheliometry which was never regarded as absolute. This scale, arbitrarily chosen at first, was maintained by an occasional intercomparison of several secondary pyrheliometers, and one Crova secondary actinometer. The comparisons made to support this scale have already been given in Table 2A, Chapter II. Such a scale, if not lost by accidents or gradual deterioration of apparatus, would suffice to test the constancy, but not the absolute value of the "solar constant." More recently this arbitrary scale has been reduced to an absolute basis by comparison of the secondary pyrheliometers with the standard instrument already described. This comparison has been given in Table 2, Chapter II.

Constants of Standard Pyrheliometer.

Referring to Chapter II for the description of the standard pyrheliometer, the reader will there find that its measures depend on the area of the aperture through which the rays enter the absorbing chamber, the rate of flow and specific heat of the water which circulates about the chamber, and the rise of temperature of the water as determined by a platinum thermometer; and that the measurements are checked in every respect, except as regards the area of the entering beam, by the device of passing a measured current of electricity through a coil of wire situated in the pyrheliometer chamber, and measuring the heating effect thus produced by the same process that would be employed for solar heating.

APERTURE OF THE BEAM.

The rays pass through a circular hole in a disk of brass. This hole was turned out in an excellent lathe, leaving a knife-edged rim. After blackening by painting with a suspension of lamp black in alcohol containing a small percentage of dissolved shellac, a slightly tapering plug was inserted till it reached a fit, and its diameter at this place was measured by means of a Brown & Sharpe micrometer gage. As thus determined the diameter was 1.292 centimeters, corresponding to an area of 1.311 square centimeters. The error of this measurement of area certainly does not exceed one-tenth per cent.

RATE OF FLOW OF WATER.

The water flows from a tank at constant level through the pyrheliometer to a micrometer valve at a constant level about 2 meters below the source and about 20 cm. above the pyrheliometer. The average rate of flow is determined by weighing the escaped water at intervals upon the pan of a beam scales reading to one-half ounces. The accuracy of the average rate increases with the weight of water, and after an hour it is readily determinable to 1 part in 200. It seldom happens that a change of average rate of flow as great as one-half per cent occurs during three hours of observation.

SPECIFIC HEAT OF WATER.

Between the temperatures of 15° and 30°, within which range all the measurements with the standard pyrheliometer have been made, the specific heat of pure water differs from unity by less than three parts in a thousand. In practice, however, the water used contains air and minute quantities of salts in solution. But the weight of air dissolved by water is insignificant compared with the weight of the water, and as the salt content of the water is only 1 part in 2,000, it is also too slight to influence the specific heat appreciably.

RISE OF TEMPERATURE OF THE WATER.

The rise of temperature is measured by a platinum resistance thermometer. Four fine platinum wires, each about 2 cm. long and of about 3.4 ohms resistance, are fixed to 8 supporting platinum wires of an average length of 10 cm. each, and having a resistance at zero centigrade of 0.005 ohm per centimeter. The fine platinum wires and their supports are divided in two groups, which are immersed, respectively, in the tube through which the water enters and that through which it leaves the pyrheliometer; so that both the fine wires and their supports take up the temperature of the water, and may be treated without discrimination. Two slide wires, each of about 0.14 ohm resistance, adjusted for balancing the bridge and not affected by the temperature of the water, are annexed, respectively, to one of the warmed and one of the unwarmed platinum resistances. A resistance of 789.8 ohms having zero temperature coefficient is shunted across one of the platinum resistances not connected with the slide wires, and means are provided for diminishing this shunt by 15.42 ohms, 31.12 ohms, or 71.69 ohms, at pleasure, for the purpose of determining the sensitiveness of the platinum resistance thermometer. Deflections of a reflecting galvanometer read on a scale at 2 meters indicate the rise of temperature of the water.

Let a = the area of the aperture admitting solar radiation in square centimeters.
b = the number of grams of water delivered per minute.
d = the value of platinum resistances at 0° C.
e = the change of resistance per degree rise of temperature.
f = the resistance of each of the two slide wires.
g = the total resistance of the shunt coil.
h = the resistance of a removable part of shunt coil.
k = the deflection caused by removal of part of shunt coil.
l = the deflection caused by admission of sunlight.
t = the mean temperature of the platinum thermometer.

Then the change of resistance of one arm of the Wheatstone bridge caused by the removal of part of the shunt coil is:

$$\frac{(d+et)^2h}{(g+d+et)\ (g+d+et-h)}$$ Call this quantity u.

The change of resistance of a single arm of the bridge to produce one division deflection is: $\frac{u}{k}$ The change of resistance of half the platinum thermometer necessary to produce one division deflection is approximately

$$\frac{u}{k}\frac{1}{\left(2-\frac{f}{d+et+f}\right)}.$$

Call the quantity in parentheses v. Call $\frac{1}{a\ e}=w$.

Then the solar radiation per square centimeter per minute is:

$$\frac{u}{v}\frac{l}{k}\frac{w}{b}$$

The values of the four platinum resistances were determined by the Wheatstone bridge method, by means of from fifteen to twenty measurements of each resistance conducted at various temperatures from 0° to 43° C., as measured by a mercury thermometer calibrated by the International Bureau of Weights and Measures, and hanging with the resistances in a stirred water bath. At 0° the four coils were nearly equal and differed by less than 0.4 per cent in the greatest instance from 3.372 ohms each. The change of resistance per degree was also nearly the same for each, and differed by less than 0.8 per cent in the greatest instance from 0.01225 ohm. The measurements were free from notably discordant values, and it is believed that the probable errors of d and e are less than 0.4 per cent and 0.8 per cent, respectively. Greater accuracy than this could probably be obtained in the construction of a new instrument of the same kind. The quantities a, g, and b may be regarded as without errors comparable to these. The quantity t is readily determinable to $\frac{1}{2}$° C. The remaining values b, k, and l are all observed repeatedly at each usage of the instrument, and to the mean result in each case may be assigned a probable error of 0.5 per cent.

15000—08——6

From these values the probable error of u is 0.8 per cent; of v, 0.2 per cent; of w, 0.8 per cent; and the probable error of a determination of solar heating is 1.4 per cent.

It is possible for the energy to escape measurement in three ways—first, by diffuse reflection; second, by convection from within the chamber; third, by convection from the outside of the water jacket after being transmitted through the water. The first loss is, however, plainly negligible, for the diffuse reflection of lampblack is only 5 per cent, so that only one-fourth per cent can escape after two reflections. Owing to the form of the receiving chamber, most of the diffusely reflected rays must suffer more than two reflections before they can emerge from the front. The cone of rays which can escape by one reflection subtends only about 0.003 of a hemisphere. The total loss by diffuse reflection probably is much less than one-tenth per cent. The losses by convection from within and without the chamber are of course proportional to the rise of temperature of the exposed surfaces. This rise of temperature is diminished the greater the rate of flow of the water current. Accordingly, the errors in question may be reduced to any desired proportion of the total energy of the beam by increasing the rate of water flow, and they will be reduced to a negligible proportion of the whole, when further increase of the rate of flow produces no change in the result of measurement. This state of affairs is found to be reached when the rate of flow is a gram per second; but it is usual to employ a rate of flow somewhat greater than this.

Experience has shown, however, that there is a possibility of the water flowing through without taking up all the heat generated within the pyrheliometer chamber. Thus, when the apparatus was first used it was not uncommon for the results to fall as much as 10 per cent below the truth, and to vary irregularly among themselves. It was found that the cause lay in the irregular circulation of the water, which would flow by certain short paths through the water jacket without actually bathing the whole wall of the inner chamber. This was remedied by inserting a copper wire about 2 meters long, coiled up in a spiral, and of such a thickness as to fill the space between the inner and outer walls, and thus to compel the water to follow the spiral course of the wire. Very little difficulty has been found since this was done, excepting that occasionally bubbles of air collect at some points within, and the instrument may then read a little low. But these are readily carried along by letting the water flow rapidly for a few minutes, and after once being rushed out it will be several days before others collect in sufficient bulk to make trouble.

A means of testing the accuracy of the whole instrument is at hand, for a hollow coil of wire is permanently fixed within the pyrheliometer chamber at its rear, and a measured electric current may be caused to flow therein, so as to produce heat at a known rate. This heat is measured by the flowing water, and the "heat found" is compared with the "heat introduced." At the time of making the coil no suitable zero coefficient wire was at hand and a flat ribbon of gold was used instead. This makes it necessary to determine the resistance of the wire, as well as the current, in each experiment, so that the following arrangement is adopted. A known resistance almost exactly equal to that of the coil is put in series with it, and the fall of potential across this resistance, and also across the coil itself while the current is flowing through both, is determined by voltmeter readings.

Let m = the resistance of the heating coil.
n = the resistance of its lead wires.
o = the resistance in series.
p = the resistance of the voltmeter.
q = reading of the voltmeter across the heating coil.
r = reading of the voltmeter across the series resistance.
s = deflection of galvanometer for heat of coil when the voltmeter is shunted across the series resistance.
y = the factor for reducing electrical heating units to calories per minute $=14.32$.

Let the other symbols used with reference to solar heating have the same significance as before, excepting that in place of w use $z=\frac{1}{e}$.

Then, since the resistance of the heating coil is very nearly the same as that of the series resistance, and both are small compared with the resistance of the voltmeter, the current through the whole circuit will be almost exactly the same whether the voltmeter is shunted across the heating coil or the series resistance.

Accordingly

$$m+n=o\frac{q}{r}$$

or

$$m=\frac{oq}{r}-n$$

The current through the heating coil when the voltmeter is across the series resistance is:

$$\frac{r(o+p)}{op}$$

Accordingly the heating in calories per minute is:

$$\left(\frac{r(o+p)}{op}\right)^2\left(\frac{oq}{r}-n\right)y$$

And the heating found is:

$$\frac{u}{v}\cdot\frac{s}{k}\cdot\frac{z}{b}.$$

The quantities o and p are known to within 0.1 per cent, and n is known to about 0.1 per cent of $\frac{oq}{r}$, while the quantities q and r are determined to within 0.2 per cent, and the quantity y is known to about the same order of accuracy. From these data the probable error of determining the electrical heating is about 0.4 per cent. The probable error of the pyrheliometer determination of it is, as given before, about 1.4 per cent.

Thus a discordance of 1.5 per cent between the "heating introduced" and the "heating found" would seem probable for any single comparison. If, however, as the mean of many trials, the "heating found" should fall below the "heating introduced," still the accuracy of the instrument for solar heating would naturally be greater than such a discrepancy would indicate, because the solar heating is more directly applied to the inner wall of the pyrheliometer chamber, and therefore less likely to be lost by convection from within than that electrically supplied.

In the latter part of the month of August, 1906, six comparisons between "heating introduced" electrically and "heating found" were made on several different days, as stated in detail in Chapter II. As the mean result, 100.00 per cent of the "heat introduced" was found. All the determinations fell between 99.2 per cent and 100.8 per cent, and the probable error of the mean as computed in the usual way from the deviations was 0.2 per cent. The pyrheliometer was inclined at different angles during these determinations, and no variation of readings depending on the inclination was found.

These results seem to show that the standard pyrheliometer may be depended on to give an absolute scale for the measurement of solar radiation accurate to within 1 per cent as the mean result of a number of comparisons. Slight irregularities of the flow of the water, and unsteadiness of the galvanometer, sometimes introduce errors of 2 or 3 per cent for individual readings. With the aid of the experience now gained it is thought to be certain that a pyrheliometer of the same general type can be constructed whose accuracy will be considerably greater, both for absolute and relative measurements.

Secondary Pyrheliometers.

All the "solar-constant" measurements thus far made depend directly on the readings of secondary pyrheliometers of the kind described in Chapter II. These instruments have been frequently compared together, and being protected from dust and carefully handled, they have generally maintained very nearly a constant relative sensitiveness. Unfortunately, pyrheliometer No. I, the instrument most used during 1903, was damaged in the autumn of 1904, and the only instrument which has remained apparently unaltered since the series of "solar-constant" measures was commenced in 1902 is a Crova alcohol actinometer. As there is no claim that the readings of the secondary instruments can be reduced to the absolute scale of energy, excepting by comparing them with a standard pyrheliometer, we need consider only what sources of error exist which tend to produce a variability of reading as between one set of circumstances and another, or which are progressive with the lapse of time.

APPLICATION OF COOLING CORRECTION.

In observing with the secondary pyrheliometers, great care is taken in reading the thermometer at 0^m20^s, 2^m0^s; 2^m20^s, 4^m0^s; 4^m20^s, 6^m0^s; 6^m20^s, 8^m0^s; 8^m20^s and 10^m0^s, from the time of start; for it is the total change of the thermometer during the intervals marked off by semicolons in the text which really determines the result as usually calculated.[1] In order to make quite sure of these important readings the opening and closing of the shutter which would occur at the beginnings of even minutes are delayed a few seconds to avoid disturbing the observer's attention during readings. In the reduction of the observations the mean of the two 100-second cooling corrections observed before and after each exposure to the sun is considered to be the mean rate of cooling during the 100 seconds of sun exposure. Now, this is obviously not strictly true, for several reasons, of which the chief ones are as follows: A considerable rise of the thermometer occurs during the nearly 20 seconds after the shutter is opened at 2 and 6 minutes from the start, so that at the beginning of the 100-second observed sun exposures the cooling is more rapid than at the end of the preceding intervals of cooling; and also the thermometer falls after the end of the sun exposures before the second intervals of cooling begin. Hence the applied cooling corrections as here determined are less than the mean cooling during exposure. This error would be principally avoided if the cooling were regarded as a function of temperature rather than time, and to see whether any appreciable error is introduced by the simpler method of reduction, readings have been occasionally reduced by the better method. It proves, however, that every result would be increased by almost exactly 1 per cent, so that the ratio of two determinations is the same whether the observations are reduced one way or the other. Accordingly the simpler method is followed.

MAGNITUDE OF COOLING CORRECTION.

It might seem probable that there would be an appreciable difference of result depending on whether the cooling correction was large or small, positive or negative. To test this, two pyrheliometers were read simultaneously. One was kept substantially at the temperature of the surroundings. The other was read sometimes at the temperature of the surrounding; sometimes warmed by exposure of its disk to the sun to nearly 20° C. above the surroundings, so that the cooling correction was large; sometimes warmed in a water bath to the same high temperature, so that the cooling correction was small; and sometimes cooled to 20° below the temperature of the surroundings and read during a state of rapid rise. As a result of all these

[1] This would not be the case if the rates of cooling and rising were treated as functions of temperature rather than time.

trials there proved to be no distinguishable difference depending on the rate of cooling. The reader may find some evidence of the unimportance of the magnitude of the cooling correction given in the following table. Attention is invited especially to the readings of September 6 in this connection.

TABLE 12.—*Effect of cooling correction on pyrheliometry.*

Date and time, 1906.	Pyrheliometer No.	Rate of rise of temperature.				Mean temperature during exposure.	Per cent correction to reduce to 30°.	Ratio VI to IV.		Departures from mean of ratios $\frac{VI}{IV}$.	
		Before exposure.	After exposure.	During exposure. Observed.	During exposure. Corrected for cooling.			Uncorrected.	Corrected to 30°.	Uncorrected.	Corrected to 30°.
Aug. 31.		°	°	°	°	°					
0h 14m	VI	−0.096	−0.240	1.734	1.902	21.2	−1.2				
	IV	−0.522	−0.612	1.116	1.683	41.5	+1.5	1.131	1.100	+.036	+.005
0h 18m	VI	−0.240	−0.306	1.620	1.893	23.1	−0.9				
	IV	−0.612	−0.678	1.050	1.695	42.5	+1.6	1.117	1.090	+.022	−.005
0h 22m	VI	−0.306	−0.384	1.530	1.875	25.4	−0.6				
	IV	−0.678	−0.714	0.996	1.692	43.0	+1.7	1.108	1.083	+.013	−.012
1h 36m	VI	0.000	−0.168	1.764	1.848	28.1	−0.2				
	IV	−0.054	−0.228	1.542	1.683	26.0	−0.5	1,098	1.102	+.003	+.007
1h 40m	VI	−0.168	−0.318	1.596	1.839	31.1	+0.1				
	IV	−0.228	−0.360	1.380	1.674	28.5	−0.2	1.099	1.102	+.004	+.007
1h 44m	VI	−0.318	−0.426	1.440	1.812	33.5	+0.4				
	IV	−0.360	−0.462	1.254	1.665	30.0	0.0	1.089	1.093	−.006	−.002
2h 40m	VI	−0.192	−0.402	1.404	1.701	38.3	+1.1				
	IV	−0.102	−0.264	1.422	1.605	20.5	−1.3	1.060	1.086	−.035	−.009
2h 44m	VI	−0.402	−0.546	1.242	1.716	40.2	+1.3				
	IV	−0.264	−0.354	1.278	1.587	23.0	−0.9	1.081	1.105	−.014	+.010
2h 48m	VI	−0.546	−0.636	1.122	1.713	41.2	+1.4				
	IV	−0.354	−0.402	1.218	1.596	24.5	−0.8	1.074	1.097	−.021	+.002
Mean[1]								1.095	1.095		
Sept. 6.											
3h 8m	VI	−0.096	−0.300	1.668	1.866	33.5	+0.4				
	IV	+0.204	+0.030	1.854	1.737	11.0	−2.5	1.074	1.106	−.013	−.002
3h 12m	VI	−0.300	−0.456	1.488	1.866	36.0	+0.8				
	IV	+0.030	−0.102	1.686	1.722	14.5	−2.0	1.084	1.114	−.003	+.006
3h 50m	VI	−0.078	−0.270	1.584	1.758	31.3	+0.2				
	IV	−1.068	−0.924	0.618	1.614	25.0	−0.7	1.090	1.100	+.003	−.008
3h 54m	VI	−0.270	−0.420	1.416	1.761	34.0	+0.5				
	IV	−0.924	−0.822	0.726	1.599	25.0	−0.7	1.101	1.114	+.014	+.006
Mean[1]								1.087	1.108	.014	.006

[1] Pyrheliometer VI was freshly blackened on September 6. Since Pyrheliometer VI was above 30° and Pyrheliometer IV below 30° during all the observations given for September 6, the mean uncorrected ratio is decidedly below its ordinary value, at this time, and the departures from it are much less than they would have been had observations under other temperature conditions been included, as on August 31.

TEMPERATURE OF THE INSTRUMENT.

A large number of comparisons were made between pyrheliometers II, IV, and VI to determine the effect of temperature upon the results. Over fifty comparisons were made between No. IV and No. VI, during which the latter was usually between 25° and 35° and the former was varied in temperature from 10° to 45°. It was found that the sensitiveness of both No. IV and No. VI diminishes at the rate of 0.13 per cent per degree.[1] A large number of comparisons of No. II and No. IV failed to show

[1] Since pyrheliometer No. V has almost identically the same construction as No. VI, the same correction is applied to its readings.

any certain change of sensitiveness of No. II depending on its temperature, although its readings were found to be subject to larger accidental variations than those of No. IV. In Table 12 the reader may perceive how closely the comparisons of the instruments agree when the correction of 0.13 per cent per degree is applied, and the observations thereby reduced to a uniform temperature of 30°.

Several causes may be assigned which combine toward producing the temperature variation noted with No. IV and No. VI, but they seem hardly sufficient to account for the entire effect. First, the specific heat of copper increases about 0.025 per cent per degree rise of temperature. Second, the stem of the thermometer is exposed from —30° up to the temperature of observation. Suppose two apparent temperatures 10° and 11° to be observed with the stem at 30° and two others of 40° and 41° with the stem also at 30°. Then the true rise of temperature in the first instance is:

$$\{11^\circ + .000156\ (11-30)\ 41\} - \{10 + .000156\ (10-30)\ 40\} = 1.0033$$

and in the second:

$$\{41 + .000156\ (41-30)\ 71\} - \{40 + .000156\ (40-30)\ 70\} = 1.0126$$

The difference is 0.0093, indicating an apparent diminution of the sensitiveness of the pyrheliometer of about 0.031 per cent per degree between 10° and 40° under conditions very similar to those of the comparison of pyrheliometers above referred to. Third, the opening of the shutter exposes the pyrheliometer to a considerable region of sky of somewhat different radiating power from the shutter. The angular aperture of the outermost diaphragm is about 0.016, and the radiation per square centimeter per minute of a "black body" to unit solid angle is about $25 \times 10^{-12}\ T^4$ calorie. Hence if the sky were absolutely devoid of radiation and scattered light, there would be a difference of:

$$(.016)\ \{(313)^4 - (283)^4\}(24 \times 10^{-12}) = .0013$$

calorie per square centimeter per minute depending on whether the disk of the pyrheliometer was at 40° C. or 10° C. But since the sky is scattering nearly or quite as much energy inward as the pyrheliometer radiates outward, it seems certain that this effect is quite negligible compared with the 1.5 calories per square centimeter per minute received from the sun, but it may be set over against the extremely small correction to be applied for the expansion of the aperture of the pyrheliometer with rising temperature.

On the whole, then, it is easy to account for about half of the temperature correction for pyrheliometers No. IV and No. VI, but the cause of the remainder is obscure. As for No. II, since its material is principally mercury, whose change of specific heat is about equal and opposite to that of copper, and since the thermometer is exposed only from 0° upward, clearly a less temperature correction would be expected.

With the Crova alcohol actinometer there is a large and uncertain temperature correction caused by the rapid changing of the specific heat of alcohol with the temperature. As there is no means of knowing the absolute temperature of the bulb of this instrument, it is impossible to apply a correction for the change of specific heat, and as it is necessary to heat or cool the bulb frequently to secure a thread of mercury to read by, the readings are doubtless often affected by temperature errors of several per cent.

ANGLE OF EXPOSURE.

As it seemed possible that there would be a difference of reading, depending on whether the instrument inclined much or little during the exposure, a freshly silvered mirror was placed in front of pyrheliometer IV in such a way as to make a constant angle with its axis of observation, and thus for a solar zenith distance of about 45° it was possible to observe by the aid of the mirror with two positions of the pyrheliometer—one nearly vertical, the other nearly horizontal.[1] Under these circumstances a number of comparisons were made with pyrheliometer No. II, the latter being pointed directly at the sun and read simultaneously with No. IV. These comparisons were conducted on two different days, of which the results were reduced separately. Some difficulty was found, especially on the first day, in keeping No. IV correctly pointed, and the probable error of observation was somewhat larger than usual on this account. From the first day's observations it appeared that No. IV read 1.8 per cent higher when vertical than when horizontal, while the second day's work indicated, on the contrary, that No. IV read 0.7 per cent lower when vertical than when horizontal. Taking the best observations alone, no appreciable difference was shown, and it was concluded that no correction for angle of exposure was required.

DETERIORATION OF SURFACE.

Despite all care which can be taken, dust collects on the smoked surfaces of the pyrheliometers, and in time diminishes their absorbing power. Pyrheliometer VI, after six months of occasional use, was cleaned off and resmoked. After this operation it read 0.7 per cent higher than before. Pyrheliometer II after having been read frequently from May to November, 1905, occasionally read during the winter, and from May to September, 1906, and having unfortunately been left open in a laboratory during the winter months, was freed from dust by blowing upon its surface vigorously on September 9, 1906, and was then found to read 1.4 per cent higher than before.

PRESSURE OF THE AIR.

To make the observations on Mount Wilson strictly comparable with those at Washington, account should be taken of the difference of barometric pressure between the two stations. This correction is, however, very small, and indeed

[1] This ingenious device was suggested by Mr. Ingersoll.

probably negligible compared with the errors from changeability of the sky at Washington. The difference depends on the fact that a part of the solar radiation absorbed by the smoked surface of the pyrheliometer is immediately lost by convection and does not affect the thermometer at all. Since convection diminishes with diminishing pressure of air, the loss must be less on Mount Wilson than in Washington, and hence the readings at the former station must be higher on this account. No experiments have been made to determine the amount of this correction. It is not applicable to the standard pyrheliometer, because whatever loss takes place at the surface where the solar rays are first received is, in that instrument, saved by the contact of the convection and radiation streams with other portions of the hollow receiving chamber.

ACCIDENTAL ERRORS.

As already intimated, the older mercury pyrheliometers I, II, and III, are not quite as reliable for accurate readings as the improved copper disk pyrheliometers IV, V, and VI. Thus, 50 comparisons [1] between No. II and No. IV, made at various times from June, 1906, to September, 1906, had an extreme range of 4 per cent, with a probable error for a single comparison of 0.8 per cent. During the same interval 54 comparisons of No. IV and No. VI were made, which, after correction for temperature, had an extreme range of 4 per cent, with a probable error for a single comparison of only 0.5 per cent. For a single reading of No. II, therefore, the probable error is about 0.6 per cent, and for a single reading of No. IV or No. VI the probable error is 0.4 per cent.

2. SOURCES OF ERROR WITH THE SPECTROBOLOMETER.

Change of Sensitiveness during Observation.

It has not been practicable to conduct the observations at constant temperature, and accordingly the sensitiveness of the galvanometer and bolometer has been subject to slight alterations as the temperature changed. These temperature effects generally tend to diminish the sensitiveness as the temperature rises, but the controlling factor appears to be the change of the magnetic field of the galvanometer, and this being the combination of the field of the earth with the fields of two steel magnets, its direction and magnitude can not readily be predicted. Probably the effect is partly produced by the differing temperature coefficients of the magnets, but the diurnal change of the intensity of the earth's field is not without importance. In addition to these various temperature effects there is also the possibility of change of the transmitting power of the optical apparatus, due to the change of inclination of the cœlostat mirrors, the collection of dust, the deteriora-

[1] A single comparison here includes one exposure to the sun for 100 seconds, with its appropriate cooling corrections. The observations of pyrheliometers No. IV and No. VI were corrected for temperature.

tion of silver, etc. Considering the complexity of the thing, it has seemed better to correct for the resultant of all these effects and not to determine corrections for each element separately. Accordingly, after multiplying the ordinates of the bolographic curves by factors representing approximately the relative transmission of the apparatus at the several wave-lengths, the areas of the corrected curves have been compared with the simultaneously observed pyrheliometer readings, and thereby a series of factors have been computed to reduce the bolometric observations of each day to a common scale of sensitiveness. For the Mount Wilson observations of 1905 the average range of the corrections during a determination of the "solar constant" amounted to 6.4 per cent, and the change of sensitiveness tended to decrease the ordinates of bolographs taken toward noon. During 1906 the average range of the correction factors was 5.2 per cent. At Washington the average range of the corrections has been 7.7 per cent. Notwithstanding the greater constancy of temperature of the observing room on Mount Wilson in 1906, as compared with 1905, due to shielding the whole building and all the ground near it from the sun, doubly sheathing the building itself, and inclosing the galvanometer and its control magnets in a cotton-stuffed box, very little decrease in range of the correcting factors occurred. This leads to the impression that the effect is probably mainly due to the diurnal change of the earth's magnetic field.

Position of Recording Spot on the Galvanometer Scale.

In ordinary galvanometer practice it is necessary for accurate work to correct the deflection for change of position along the scale of the galvanometer. This correction has not been applied here; first, because the deflections are small, never exceeding 20 cm. on a scale at 1.5 meters from the galvanometer, and, second, because it is only changes of a centimeter or two in position which count in the bolographic work. For it is not the ratio of deflections of 20 cm. to others of 2 cm. with which we are concerned in the more important measurements, but rather ratios of deflections of perhaps 15 cm. to others of 16 cm., and of deflections of perhaps 2 cm. to others of 3 cm., so that the changes of scale value are insignificant in importance. It is only in determining the exact form of the solar spectrum energy curve that the scale correction would be appreciable, and so far as determinations of the "solar constant" are concerned, errors of 10 per cent in estimating the exact form of the energy curve would make but a slight difference in the result, as will be shown below.

Absorption of the Optical Apparatus.

The bolographic energy curve does not give immediately the distribution of radiation in the spectrum of the solar ray as it reaches the earth's surface, for the form of the curve is modified considerably by the absorption of the optical apparatus.

Let $a_1\ a_2\ .\ .\ .\ .\ .\ a_p$ be the transmission of the rays through the atmosphere at zenith sun.

Let $b_1\ b_2\ .\ .\ .\ .\ .\ b_p$ be the ordinates of a bolographic curve proportional to the intensity of these rays as they affect the bolometer.

Let $c_1\ c_2\ .\ .\ .\ .\ .\ c_p$ be multipliers to correct the ordinates of the curves for the absorption of the apparatus.

Let $h_1\ h_2\ .\ .\ .\ .\ .\ h_p$ be the ordinates when corrected for the absorption of the apparatus and the atmosphere.

Let m be the secant of the sun's zenith distance.[1]

Let R be the total intensity of the solar ray at the earth's surface.

Let r and r_o be the actual and mean solar distances, respectively.

Let S be the "solar constant."

Then

$$S=\left(\frac{r}{r_o}\right)^2\left\{\frac{R}{b_1c_1+b_2c_2+\ldots b_pc_p}\right\}\left\{\frac{b_1c_1}{a_1{}^m}+\frac{b_2c_2}{a_2{}^m}+\ldots\frac{b_pc_p}{a_p{}^m}\right\}$$

Differentiating this expression with regard to c_n and dividing the result by the original expression we have:

$$\frac{\delta\ S_{(c_n)}}{S}=\frac{b_nc_n}{\Sigma(bc)}\left\{\frac{\Sigma\ (b\ c)}{a_n{}^m\ \Sigma\left(\frac{b\ c}{a_m}\right)}-1\right\}.\frac{\delta c_n}{c_n}.$$

And

$$\frac{\delta S_c}{S}=\sqrt{\sum_{n=o}^{n=p}\left[\left(\frac{b_nc_n}{\Sigma(bc)}\right)^2.\left\{\frac{\Sigma(bc)}{a_n^m\Sigma\left(\frac{bc}{a^m}\right)}-1\right\}^2.\left(\frac{\delta c_n}{c_n}\right)^2\right]}$$

For certain rays near the orange part of the spectrum the expression

$$\left\{\frac{\Sigma(bc)}{a_n^m\Sigma\left(\frac{bc}{a^m}\right)}-1\right\}$$

is nearly zero, and at the extreme violet and the extreme infra-red the value of $\frac{b\ c}{\Sigma(bc)}$ is nearly zero. Accordingly it is evident that for rays near the middle and two extremes of the spectrum gross errors in the determination of the absorption of the apparatus will produce no effect on the value of the "solar constant." It is not difficult to measure the relative absorption of the apparatus to within 5 per cent from wave-length 0.45μ to wave-length 2.5μ, and in the remaining violet part of the spectrum the error of measurement will hardly reach 10 per cent. Assuming probable errors of the above magnitudes in the regions of spectrum indicated, it is found by computation that the probable error of the "solar con-

[1] For simplicity in this demonstration the small change of zenith distance during the time of taking a bolograph is here neglected.

stant," as determined from Mount Wilson observations of September 20, 1906, due to uncertainty of the absorption of the spectrobolometric apparatus, is 0.14 per cent.

As the quantity b enters the expression in the same way as c, the effect of the very small errors of measurement of b, and also of the error which is made in assuming the area of a bolograph proportional to the sum of the n measured ordinates, will evidently be negligible.

Form of the Energy Curve Outside the Atmosphere.

Using the same notation as before, the "solar constant" may be expressed as follows:

$$S=\left(\frac{r}{r_o}\right)\left(\frac{R}{\Sigma(bc)}\right)\Sigma h$$

In this expression $\frac{R}{\Sigma(bc)}$ is to be regarded as a constant which could be determined from any bolograph taken in connection with a pyrheliometer reading made simultaneously.

We then have:

$$\frac{\delta S(h_n)}{S}=\frac{h_n}{\Sigma h}\cdot\frac{\delta h_n}{h_n}.$$

The quantity h_n is determined by plotting the values of $\log_{10} b_n$ with the air masses for the several bolographs as abscissæ. Such plots determine straight lines whose equation is of the form:

$$\log_{10} b=m \log_{10} a+\log_{10} h.$$

It can be shown in accordance with the principles of Least Squares that the probable error of

$$(\log_{10} h)=.67\sqrt{\frac{(\Sigma m^2)\{\Sigma(\delta(\log_{10} b))^2\}}{(n-2)\{n\Sigma m^2-(\Sigma m)^2\}}}$$

where $\Sigma(\delta(\log b))^2$ represents the sum of the squares of the residuals of the ordinates of the plot from the best straight line.

It may also be shown that the probable error of $(\log_{10} h)=(\log_{10} e)\frac{\delta h}{h}$, where δh is the probable error of h, and e is the Napierian base.

Substituting values we have:

$$\frac{\delta S(h_n)}{S}=1.55.\frac{h_n}{\Sigma h}\sqrt{\frac{(\Sigma m^2)\{\Sigma(\delta(\log_{10} b))^2\}}{(n-2)\{n\Sigma m^2-(\Sigma m)^2\}}}$$

and

$$\frac{\delta S_h}{S}=1.55\sqrt{\Sigma\left[\left(\frac{h}{\Sigma h}\right)^2\left\{\frac{(\Sigma m^2)\{\Sigma(\delta(\log_{10} b))^2\}}{(n-2)\{n\Sigma m^2-(\Sigma m)^2\}}\right\}\right]}$$

For a representative day of observation on Mount Wilson, September 20, 1906, the average probable error of h was found to be 1.2 per cent, and the probable error of the "solar constant" caused by errors of h was 0.17 per cent. There is an apparent discrepancy between the two numerical results just given; but this is due to the fact that the average value of $\frac{\delta h}{h}$ is greatly raised by the smallness of the values of h, and the difficulties of measurement near the ends of the spectrum. These parts of the spectrum contain but a small fraction of the total energy, however, so that the inaccuracy of observing them plays little part in the final result.

Final Probable Error of a "Solar-Constant" Determination.

In finding the complete probable error of a determination of the "solar constant" it will be assumed the ratio of actual to mean solar distance is known without sensible error, and that errors of air mass and ordinates of bolographs are fully taken account of in the determinations of residuals of ordinates in the logarithmic plots. It is apparent that the error due to defects of pyrheliometry may have two different values according as we deal with relative or absolute determinations of the "solar constant", but in either case the "solar constant" will be affected by the same percentage error as the pyrheliometer measurement, on account of defects of pyrheliometry.

Accordingly, we have the following expression for the total probable error of a "solar-constant" determination:

$$\frac{\delta S}{S}=\sqrt{\left(\frac{\delta S_R}{S}\right)^2+\left(\frac{\delta S_c}{S}\right)^2+\left(\frac{\delta S_h}{S}\right)^2}$$

In substituting the values of the quantities under the radical sign, the value $\frac{\delta S_R}{S}$ proper to a single pair of pyrheliometer measurements will be used, because the different groups of observations of the pyrheliometer can not be regarded as supporting each other, because they are used separately to reduce the indications of the bolometer to normal sensitiveness.

Substituting the values already found for the quantities under the radical sign, the relative probable error of a representative determination of the "solar constant" on Mount Wilson is

$$\sqrt{\frac{(0.4)^2}{2}+(0.14)^2+(0.17)^2}$$

or 0.36 per cent.

The probable error of a determination reduced to actual calories per square centimeter per minute is

$$\sqrt{(1.4)^2+(0.36)^2}$$

or 1.45 per cent.

In view of the results just reached, we may expect that the determinations of the solar constant made from Mount Wilson observations of good quality, will very seldom differ from one another by as much as 1.5 per cent, or 0.03 calorie, unless there is an actual variation of the intensity of solar radiation to cause departures greater than this.

The values to be given in Chapter V will be based on the provisional scale of pyrheliometry heretofore employed here and will not be corrected to the standard scale of calories furnished by the continuous-flow pyrheliometer, because the correction amounts to only one part in seventy-four, apparently, and as shown above there is still an uncertainty of about the same order as to the exact amount of it.

Chapter V.

RESULTS OF MEASUREMENTS OF THE INTENSITY OF SOLAR RADIATION.

SUMMARY OF THE OBJECTS, METHODS, AND ACCURACY OF THE INVESTIGATION.

In the preceding chapters have been given the details of the means and methods adopted and the degree of accuracy to be expected in these measurements of the intensity of the solar radiation. The numerical results obtained will be stated in the present chapter; but in order that the reader may more easily grasp their exact significance a brief summary of the aim, method, means of measurement, and probable accuracy of the investigation may well preface the statement of the actual results. For further details the reader is invited to consult the more extended statements already given.

The aim of the investigation is to determine the mean intensity of solar radiation which reaches the planet earth, and the alteration in quality and quantity to which the solar radiation is subject during its passage through the atmosphere toward the surface of the earth, apart from the obstruction offered by visible clouds.

The method of investigation comprises measurements of the total intensity of the solar beam as it reaches the earth's surface, combined with other measurements adapted to enable us to form an estimate of the losses which occur in the atmosphere. This latter estimate depends on observing the alteration of intensity of the rays of different wave-lengths accompanying the change of length of path of the rays within the atmosphere from the time when the sun is near the horizon to the time when it is near the zenith. As recognized by Radau, and acted upon by Langley, it is necessary to treat the different spectral rays separately in forming this estimate, because they are differently affected by the atmosphere in transmission. Accordingly, the method used here, which is substantially that of Langley, involves not only the measurement of the total intensity of the solar beam at the earth's surface, but also the measurement of the intensity at different altitudes of the sun of the rays of different wave-lengths.

Inasmuch as a nearly constant state of transparency of the atmosphere within the time occupied by a single half day of observation is indispensable to success in estimating the transmission of the atmosphere, it has been found best to conduct many of the observations at an elevated station little subject to cloudiness, and this station, by invitation of Professor Hale and President Woodward, of the Carnegie Institution, has been at the Carnegie Solar Observatory on Mount Wilson in California. Observations have been carried on at Washington also whenever the conditions of sky permitted, and there have been several occasions when the observations were satisfactorily conducted on the same day at Washington and at Mount Wilson; so that a check upon the accuracy of the results is obtained by comparing the intensity of the solar radiation outside the atmosphere as computed from Washington observations with that computed from Mount Wilson observations. Such a comparison will be found in section 2 of Chapter VI. In such instances the intensity of radiation actually observed at Washington near the sea-level is only about three-fourths as great as that observed on Mount Wilson, at more than one mile above sea-level; so that the estimation of the transmission of the air must give very different results in the two cases if the final result outside the atmosphere is to be the same, and therefore this test of the accuracy of the method is particularly severe.

The exponential formula $e=e_0a^{\sec z}$, of Lambert and of Bouguer, has been employed in estimating the transmission of the air for each separate wave-length of radiation. When applied in this manner, i. e., for homogeneous rays, this formula appears theoretically sound, provided the earth's atmosphere may be regarded as approximately composed of layers nearly concentric with the earth, which, while differing in transparency in any manner, as between one layer and another, are, each one by itself alone, of uniform and constant transparency throughout in the region which is involved in the transmission of the solar beam during the three or four hours of a single half day of observation. It is believed that this condition is often satisfied by the atmosphere above Mount Wilson and occasionally by that above Washington.

For measuring the total intensity of the solar radiation at the earth's surface, a simple form of secondary pyrheliometer has been developed here from the mercury pyrheliometer of Tyndall, itself improved from the water pyrheliometer of Pouillet. Several specimens of this instrument and two specimens of the alcohol actinometer of Crova have been employed, and have been repeatedly compared with each other during the several years over which the work has extended. There is here employed a secondary scale of measurement preserved and verified by these frequent comparisons. This secondary scale is not believed to be the absolute scale of calories, whose unit may be stated to be that intensity of radiation which, if totally absorbed at normal incidence upon a surface of 1 square centimeter area, would suffice in one minute to warm one gram of water at its temperature of maximum density through one degree centigrade. Our secondary scale probably does not differ from this absolute scale by more than 2 per cent; and as there is not yet entire certainty as to the factor of reduction to convert this secondary scale to absolute calories, the results will be stated in units of the secondary scale.[1]

For measuring the intensity of the different spectral rays the spectrobolometer has been employed, and its indications have been automatically recorded in the manner devised about 1890 by Langley. The arrangements are such that a curve exhibiting the relative intensity of the energy of the spectrum for all wave-lengths between 0.37μ in the violet and 2.8μ in the infra-red is obtained in about 11 minutes of time. Such energy curves are obtained as often as possible while the sun is low, and once in half an hour, or thereabouts, for moderate and high altitudes of the sun, so that the whole progress of the variation of radiation as dependent on the length of path in the air is determinable for each separate day of observation. Generally at least eight energy curves a day are measured to determine the transmission of the air. Measurements are made of the ordinates of each of these energy curves at 44 different wave-lengths. Corrections are applied to allow for the selective absorption of the optical apparatus employed, and for variations of sensitiveness of the bolometric apparatus. The measurements are reduced to the scale of pyrheliometry above mentioned by comparing the total area included under each corrected energy curve, or, in other words, the summation of the energy as it is found in the spectrum, with the total energy of the ordinary beam of sunlight as simultaneously determined by the readings of the pyrheliometer. Thus is obtained a factor by means of which the energy of the spectrum, as determined by the bolometer, may be reduced to calories. From the eight or ten measurements of intensities at each of 44 wave-lengths in the spectrum, taken together with the known change of path of the solar rays during the time elapsed between the observations, the relative intensities which would be found in the spectrum, if it could be examined beyond the atmosphere, are inferred as illustrated in Chapter III and in Plate XIV; and also the atmospheric transmission is determined for each of the 44 different wave-lengths. The factor obtained, as stated above, by comparison with pyrheliometry, enables the total energy of the spectrum beyond the atmosphere to be reduced to calories.

By this complex process we have derived from numerous days of observation at Washington and at Mount Wilson the following principal results: (1) The total intensity of radiation which reaches the earth's surface at different altitudes of the sun. (2) The transmission of a vertical column of the atmosphere for each of 44 different wave-lengths of the solar spectrum between 0.37μ and 2.8μ. (3) The total intensity of the solar radiation as it would be found outside the atmosphere at the earth's mean distance from the sun. Other results of the work will be mentioned in their places.

[1] See, however, the comparison between secondary and standard pyrheliometers given in Table 2, Chapter II.

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The results (1) and (2) have a local character, but will nevertheless serve to promote studies of the dependence of the earth's temperature upon the solar radiation, as shown in Part II. The mean intensity of the total solar radiation as it would be found outside the atmosphere is a "constant of nature" having general significance. If we are not deceived, the numerous determinations of it made on Mount Wilson are comparable one with another, and are not often subject to accidental relative errors of more than 1 per cent. The Washington observations only rarely reach the same standard of accuracy, but for the best Washington days there is believed to be small probability of uncertainty greater than 3 per cent. As stated above, all the results are given on a provisional scale of radiation which may prove to be 1 or 2 per cent above the true one. We now proceed to give the results in detail.

PYRHELIOMETER MEASUREMENTS.

In the following Table 13 are included all the more important pyrheliometer observations made at Washington and Mount Wilson since 1902. The Washington observations are kept separate from those at Mount Wilson. With each day of observation is given the initials of the observer and the Roman numeral designating the instrument employed. Following these is given the factor employed to reduce the readings to the scale of approximate calories, in terms of which all determinations of the solar radiation outside the atmosphere will appear in a later table. Thus, if the number 0.8102 is given as a factor all the readings below are to be multiplied by it to reduce to approximate calories. Following this is given in parallel columns the corrected rise of temperature per minute of the pyrheliometer, and the secant of the zenith distance of the sun at the mean time of each observation. In stating the rise of temperature per minute, the values observed with pyrheliometers IV, V, and VI have been corrected to correspond to a temperature of the pyrheliometer of 30° C.

On several of the days of observation two or more different pyrheliometers were observed nearly simultaneously. When the readings were strictly simultaneous and made solely for fixing the ratio of readings of different instruments the ratio of the results is given in Table 2A, Chapter II, from which values of sec. Z are omitted. In other cases the readings will be found in Table 13. The comparisons included in Table 2A, Chapter II, furnish the evidence on which depends our belief in the approximate constancy of our scale of pyrheliometry during the several years in which it has been employed. On some of the days included in the tables, Mr. H. H. Kimball, of the United States Weather Bureau, observed with the Ångström electrical compensation pyrheliometer, nearly simultaneously and close by, and when his observations shall be published by the Weather Bureau a comparison of the readings may be made by those interested.

Table 13.—*Pyrheliometer readings.*

MOUNT WILSON, CALIFORNIA.

[Elevation, 1,780 meters.]

1905.

May 14, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.848	2.009
1.872	1.962
1.995	1.424
2.004	1.402
1.992	1.323
2.007	1.308
2.061	1.209
1.863	1.197
2.046	1.170
2.058	1.159
2.100	1.069
2.112	1.067
2.085	1.043
2.058	1.043
2.040	1.113
2.067	1.120
1.974	1.177
1.965	1.189
1.968	1.282
1.887	1.297
2.028	1.312
1.944	1.449
1.953	1.470
1.914	1.573
1.848	1.603
1.917	1.763
1.887	1.800
1.830	1.927
1.752	1.973
1.776	2.283
1.788	2.354
1.710	2.638
1.713	2.738
1.635	3.066
1.623	3.207
1.434	4.747
1.404	5.039

May 15, a. m. and p. m. C. G. A, L. R. I. II. .764

R.	Sec. Z.
1.692	2.932
1.716	2.820
1.755	2.444
1.785	2.364
1.872	2.068
1.962	1.715
1.944	1.684
2.010	1.415
2.007	1.394
2.082	1.236
2.073	1.226
2.088	1.126
2.091	1.119
2.109	1.062
2.124	1.058
2.106	1.039
2.067	1.038
2.022	1.092
2.049	1.099
1.950	1.300
1.959	1.316
1.890	1.614
1.905	1.644
1.536	3.284
1.533	3.442

May 16, a. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.677	2.889
1.710	2.775
1.836	2.442
1.815	2.368
1.890	1.986
1.896	1.936
1.998	1.603
1.977	1.578
2.043	1.323
2.058	1.308
2.013	1.160
1.950	1.156
2.046	1.056
2.097	1.053
2.103	1.040
2.073	1.040

May 17, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.710	3.140
1.710	3.015
1.797	2.625
1.812	2.540
1.863	2.215
1.866	2.155
1.911	1.955
1.935	1.910
2.028	1.572
2.028	1.545
2.082	1.400
2.049	1.380
2.073	1.282
2.067	1.267
2.076	1.173
2.130	1.162
2.166	1.112
2.139	1.107
2.136	1.072
2.127	1.069
2.079	1.040
2.082	1.039
2.112	1.055
2.088	1.058
2.082	1.141
2.040	1.150
1.935	1.299
1.959	1.316
1.902	1.566
1.905	1.593
1.803	1.968
1.797	2.016
1.725	2.460
1.722	2.542
1.605	3.040
1.566	3.175

May 18, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.686	2.680
1.674	2.591
1.776	2.283
1.776	2.220
1.908	1.648
1.905	1.619
1.992	1.492
2.001	1.469
2.010	1.279
2.037	1.267
2.049	1.121
2.058	1.114
2.097	1.054
2.091	1.051
2.034	1.036
2.058	1.037
2.034	1.119
2.028	1.127
2.016	1.290
1.984	1.303
1.854	1.641
1.833	1.673
1.707	2.219
1.656	2.283
1.545	2.729
1.560	2.833

May 19, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
0.864	....
0.954	....
1.011	....
1.047	5.260
1.122	4.900
1.365	3.480
1.380	3.330
1.509	2.822
1.551	2.719
1.641	2.382
1.644	2.315
1.872	1.554
1.872	1.530
1.941	1.359
1.920	1.341
1.974	1.181
1.968	1.173
1.950	1.068
2.010	1.064
1.971	1.045
2.011	1.041
2.004	1.034
1.974	1.035
1.989	1.140
1.989	1.149
1.911	1.388
1.896	1.407
1.818	1.681
1.821	1.712
1.716	1.988
1.713	2.040
1.560	2.472
1.572	2.558
1.398	3.146
1.338	3.287
1.107	5.000
1.110	5.360

May 20, a. m. L. R. I. II. .764

R.	Sec. Z.
1.830	2.148
1.833	2.088
1.962	1.644
1.980	1.614
2.040	1.358
2.040	1.340
2.115	1.088
2.127	1.082
2.112	1.037
2.127	1.038

May 23, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.713	2.843
1.701	2.742
1.773	1.663
1.845	1.629
1.977	1.526
1.995	1.501
2.070	1.188
2.070	1.178
2.100	1.110
2.127	1.106
2.118	1.028
2.097	1.029
2.025	1.127
2.040	1.138
1.818	1.803
1.830	1.844
1.737	2.182
1.710	2.248
1.587	2.792
1.554	2.895

May 24, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.566	3.310
1.587	3.162
1.692	2.702
1.683	2.608
1.818	2.106
1.803	2.056
1.968	1.514
1.959	1.488
2.013	1.254
2.013	1.241
2.058	1.060
2.064	1.058
2.034	1.109
2.061	1.114
1.806	2.093
1.824	2.152
1.590	3.535
1.491	3.715

May 25, a. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.674	2.796
1.686	2.686
1.779	2.413
1.779	2.342
1.821	2.103
1.848	2.051
2.013	1.488
2.022	1.464
2.055	1.196
2.097	1.183
2.136	1.050
1.985	1.048

June 6, a. m. and p. m. C. G. A., L. R. I. II. .764

R.	Sec. Z.
1.972	1.982
1.978	1.932
2.064	1.488
2.058	1.465
2.097	1.198
2.103	1.186
2.148	1.079
2.157	1.073
2.172	1.026
2.112	1.025
2.130	1.027
2.121	1.028
2.100	1.107
2.091	1.111
2.091	1.189
2.073	1.197
2.130	1.327
2.085	1.347
2.037	1.557
2.043	1.582
1.968	1.980
1.953	2.033
1.851	2.580
1.884	2.670

June 7, a. m. L. R. I. II. .764

R.	Sec. Z.
1.551	4.42
1.593	4.18
1.761	2.918
1.776	2.804
1.875	2.197
1.890	2.133
2.067	1.378
2.100	1.365
2.109	1.238
2.121	1.222
2.151	1.072
2.193	1.071
2.100	1.023
2.043	1.022

June 13, p. m. L. R. I. II. .764

R.	Sec. Z.
2.205	1.107
2.148	1.113
2.205	1.180
2.223	1.190
2.121	1.260
2.160	1.275
2.136	1.383
2.136	1.401
2.028	1.601
2.058	1.632
2.004	1.935
2.007	1.987
1.896	2.335
1.857	2.405

June 14, a. m. and p. m. L. R. I. II. .764

R.	Sec. Z.
1.686	4.000
1.713	3.813
1.776	3.280
1.803	3.150
1.863	2.752
1.857	2.660
1.935	2.298
1.947	2.237
2.109	1.412
2.109	1.392
2.118	1.308
2.133	1.290
2.163	1.111
2.151	1.103
2.178	1.042
2.175	1.039
2.193	1.022
2.142	1.119
2.106	1.123
2.094	1.215
2.100	1.230
2.103	1.360
2.079	1.379
2.004	1.697
2.022	1.730
1.938	2.115
1.902	2.177
1.836	2.682

June 17, a. m. L. R. I. II. .764

R.	Sec. Z.
1.737	3.000
1.749	2.890
1.842	2.460
1.857	2.385
1.923	1.990
1.953	1.942
2.079	1.430
2.073	1.411
2.103	1.298
2.103	1.281
2.109	1.185
2.115	1.172
2.139	1.100
2.139	1.096
2.112	1.040
2.151	1.040
2.145	1.028
2.181	1.028
2.142	1.025
2.184	1.025

June 20, p. m. L. R. I. II. .764

R.	Sec. Z.
2.082	1.102
2.115	1.110
2.049	1.214
2.049	1.227
1.995	1.420
1.992	1.443
1.914	1.654
1.914	1.688
1.818	1.925
1.848	1.973
1.785	2.219
1.782	2.283

June 23, a. m. L. R. I. II. .764

R.	Sec. Z.
1.797	3.545
1.833	3.385
1.899	2.798
1.926	2.695
1.965	2.303
1.986	2.237
2.118	1.428
2.139	1.408
2.127	1.272
2.163	1.259
2.205	1.168
2.172	1.159
2.172	1.078
2.214	1.072
2.244	1.053
2.196	1.051

June 26, p. m. L. R. I. II. .764

R.	Sec. Z.
2.130	1.188
2 118	1.199
2.109	1.248
2.067	1.260
2.091	1.349
2.127	1.369
2.073	1.552
2.013	1.580
1.995	1.755
1.980	1.793
1.941	2.061
1.959	2.113

June 28 a. m. L. R. I. II. .764

R.	Sec. Z.
1.869	2.852
1.887	2.746
1.932	2.442
1.941	2.365
1.977	2.066
1.988	2.013
2.166	1.210
2.163	1.200
2.133	1.125
2.166	1.117
2.205	1.060
2.199	1.057
2.196	1.030
2.196	1.029

July 1, a. m. L. R. I. II. .764

R.	Sec. Z.
1.713	3.670
1.743	3.500
1.806	2.932
1.809	2.829
1.893	2.370
1.917	2.303
1.953	2.122
1.965	2.068
2.097	1.834
2.130	1.796

TABLE 13.—*Pyrheliometer readings*—Continued.

MOUNT WILSON, CALIFORNIA.

[Elevation, 1,780 meters.]

July 3, a. m.
L. R. I.
II. .764

R.	Sec. Z.
1.800	3.170
1.824	3.038
1.893	2.630
1.899	2.540
1.935	2.147
1.971	2.093
2.088	1.408
2.097	1.388
2.109	1.250
2.122	1.237
2.076	1.108
2.136	1.100
2.133	1.063
2.121	1.059
2.139	1.029
2.157	1.028

July 6, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.145	1.219
2.145	1.229
2.100	1.320
2.079	1.335
2.043	1.453
2.037	1.473
1.986	1.642
1.986	1.673
1.926	1.847
1.908	1.888
1.863	2.122
1.860	2.180

July 10, a. m.
L. R. I.
II. .764

R.	Sec. Z.
1.434	4.10
1.479	3.89
1.656	2.76
1.674	2.670
1.782	2.206
1.773	2.151
1.959	1.484
1.986	1.462
2.013	1.270
2.016	1.254
2.037	1.170
2.046	1.148

July 11, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.139	1.093
2.124	1.101
2.055	1.156
2.094	1.164
2.061	1.261
2.034	1.273
2.022	1.512
2.004	1.538
1.947	1.822
1.923	1.862
1.851	2.110
1.854	2.165

July 12, a. m.
L. R. I.
II. .764.

R.	Sec. Z.
1.644	3.320
1.659	3.190
1.737	2.585
1.788	2.510
1.836	2.258
1.857	2.192
2.031	1.429
1.995	1.407
2.049	1.260
2.055	1.248
2.082	1.136
2.106	1.128
2.082	1.092
2.073	1.083

July 19, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.085	1.140
2.127	1.148
2.094	1.218
2.115	1.230
2.058	1.358
2.031	1.377
1.974	1.528
1.980	1.556
1.962	1.836
1.941	1.878
1.827	2.168
1.869	2.230
1.800	2.480
1.761	2.560

July 21, a. m.
and p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.136	1.251
2.169	1.239
2.199	1.148
2.172	1.133
2.217	1.059
2.280	1.057
2.052	1.393
2.010	1.412
2.001	1.557
1.947	1.587
1.905	1.846
1.881	1.884
1.839	2.121
1.827	2.183
1.767	2.480
1.746	2.560

July 22, a. m.
L. R. I.
II. .764

R.	Sec. Z.
1.581	4.400
1.608	4.150
1.755	3.270
1.752	3.133
1.851	2.655
1.821	2.568
1.947	2.175
1.947	2.117

July 25, a. m.
and p. m.
L. R. I.
II. .764

R.	Sec. Z.
1.626	2.790
1.647	2.700
1.746	2.285
1.722	2.217
1.920	1.492
1.914	1.478
1.980	1.308
1.986	1.292
2.013	1.157
2.010	1.148
2.049	1.062
2.022	1.060
2.058	1.034
2.058	1.035
1.977	1.110
1.992	1.117
1.971	1.179
1.989	1.188
1.988	1.382
1.977	1.400
1.914	1.578
1.899	1.610
1.818	1.920
1.821	1.972
1.743	2.232
1.746	2.302
1.668	2.700

July 28, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.115	1.100
2.127	1.103
2.097	1.171
2.022?	1.181
2.061	1.243
2.085	1.260
2.001	1.371
1.986	1.390
1.965	1.567
1.998	1.592
1.914	1.940
1.920	1.983
1.818	2.302
1.821	2.373
1.764	2.760
1.725	2.870

July 31, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.118	1.125
2.139	1.133
2.097	1.212
2.115	1.224
2.037	1.300
2.067	1.318
1.986	1.490
1.989	1.513
1.953	1.674
1.908	1.709
1.887	1.878
1.917	1.921
1.806	2.152
1.833	2.213
1.791	2.525
1.773	2.606
1.677	2.977
1.677	3.090

Aug. 3, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.169	1.127
2.157	1.133
2.097	1.213
2.145	1.227
2.121	1.300
2.085	1.316
2.061	1.401
2.076	1.422
2.061	1.604
2.013	1.644
2.046	1.680
1.971	2.004
1.950	2.053
1.890	2.328
1.866	2.400
1.821	2.765
1.791	2.870

Aug. 9, p. m.
L. R. I. C. G. A.
II. .764

R.	Sec. Z.
1.974	1.116
1.944	1.122
1.917	1.237
1.965	1.248
1.893	1.348
1.857	1.362
1.819	1.588
1.830	1.618
1.800	1.722
1.785	1.757
1.692	2.070
1.659	2.139
1.614	2.410
1.635	2.489
1.515	2.940
1.503	3.065

Aug. 10, a. m.
and p. m.
L. R. I., C. G. A.
II. .764

R.	Sec. Z.
1.770	3.263
1.806	3.133
1.890	2.602
1.887	2.517
1.911	2.286
1.953	2.218
2.100	1.510
2.127	1.486
2.091	1.353
2.154	1.338
2.145	1.272
2.145	1.259
2.139	1.169
2.133	1.160
2.115	1.065
2.136	1.065
1.425	4.315
1.377	4.550

Aug. 11, a. m.
and p. m.
L. R. I., C. G. A.
II. .764

R.	Sec. Z.
1.650	3.900
1.665	3.715
1.725	3.110
1.725	2.982
1.827	2.487
1.851	2.403
1.878	2.182
1.902	2.122
2.004	1.523
2.031	1.498
2.058	1.300
2.049	1.286
2.079	1.243
2.082	1.233
2.103	1.140
2.112	1.130
2.139	1.100
2.142	1.097
2.154	1.061
2.160	1.061
2.118	1.058
2.127	1.058
2.118	1.158
2.100	1.167
2.085	1.198
2.127	1.208
2.055	1.301
2.079	1.317
1.953	1.598
1.968	1.628
1.917	1.820
1.911	1.858
1.839	2.182
1.833	2.248
1.764	2.690
1.731	2.792
1.572	3.450
1.551	3.618

Aug. 14, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.052	1.234
2.064	1.247
2.013	1.344
1.998	1.362
1.983	1.505
1.995	1.533
1.917	1.924
1.890	1.971
1.875	2.216
1.854	2.278
1.782	2.619
1.758	2.710
1.671	3.246
1.638	3.485

Aug. 17, a. m.
L. R. I.
II and III. .764

R.	Sec. Z.
1.677	3.790
1.740	3.600
1.794	2.870
1.779	2.762
1.854	2.420
1.872	2.342
2.019	1.550
1.992	1.523
2.037	1.332
2.034	1.314
2.062	1.223
2.086	1.210
2.092	1.150
2.038	1.141
2.043	1.071
1.995	1.071

Aug. 18, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.007	1.220
1.983	1.231
1.989	1.326
1.983	1.342
1.920	1.590
1.905	1.617
1.785	1.831
1.833	1.872
1.725	2.175
1.758	2.240
1.653	2.780
1.677	2.884

Aug. 21, p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.917	1.227
1.932	1.236
1.908	1.383
1.890	1.400
1.851	1.540
1.857	1.566
1.809	1.783
1.776	1.821
1.734	2.123
1.704	2.180
1.617	2.650
1.623	2.750

Aug. 22, a. m.
and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.608	3.818
1.626	3.650
1.737	2.772
1.764	2.677
1.971	1.576
1.959	1.551
1.989	1.383
2.004	1.365
1.977	1.258
2.025	1.249
2.052	1.081
2.040	1.080
1.959	1.380
1.908	1.400
1.932	1.530
1.938	1.556
1.881	1.746
1.896	1.780
1.836	2.062
1.821	2.118
1.734	2.525
1.743	2.615

Aug. 24, p. m.
C. G. A.,
L. R. I.
II. .764

R.	Sec. Z.
1.959	1.243
1.947	1.254
1.893	1.368
1.902	1.388
1.848	1.588
1.839	1.613
1.800	1.993
1.806	2.043
1.692	2.512
1.668	2.592
1.578	3.268
1.524	3.418
1.458	3.980

Aug. 25, a. m.
and p. m.
L. R. I.
II. .764

R.	Sec. Z.
1.515	3.950
1.551	3.780
1.614	3.220
1.632	3.100
1.746	2.552
1.743	2.468
1.959	1.636
1.923	1.606
1.968	1.397
1.983	1.379
2.043	1.210
2.049	1.200
2.052	1.090
2.058	1.090
1.992	1.210
1.986	1.220
1.971	1.443
1.956	1.465
1.893	1.793
1.872	1.832
1.725	2.553
1.728	2.647
1.629	3.100
1.632	3.220
1.443	4.500
1.404	(4.950)

Aug. 29, p. m.
L. R. I.
II. .764

R.	Sec. Z.
1.908	1.332
1.878	1.348
1.908	1.531
1.902	1.557
1.845	1.966
1.821	2.015
1.764	2.399
1.755	2.477
1.599	3.098
1.620	3.228
1.491	3.985
1.476	4.210

Aug. 30, a. m.
and p. m.
L R. I.
II. .764

R.	Sec. Z.
1.254	5.60
1.302	5.25
1.509	3.690
1.518	3.494
1.698	2.550
1.713	2.470
1.905	1.607
1.902	1.579
1.983	1.283
1.950	1.272
1.983	1.163
1.986	1.158
1.929	1.218
1.917	1.227
1.986	1.348
1.989	1.363
1.938	1.503
1.986	1.529
1.899	1.790
1.905	1.829

TABLE 13.—*Pyrheliometer readings*—Continued.

MOUNT WILSON CALIFORNIA.

[Elevation, 1,780 meters.]

1.806	2.107
1.821	2.160
1.662	2.512
1.743	2.597
1.626	3.030
1.599	3.165
1.485	3.640
1.497	3.840
1.389	4.480

Sept. 5, p. m.
L. R. I.
II. .764

R.	Sec. Z.
2.034	1.269
2.112	1.281
2.058	1.349
2.034	1.364
1.935	1.572
1.929	1.598
1.833	1.892
1.800	1.937
1.644	2.800
1.638	2.917
1.518	3.657
1.470	3.850

Sept. 8, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.542	3.143
1.578	3.003
1.719	2.431
1.731	2.356
1.839	2.008
1.833	1.960
1.872	1.724
1.902	1.693
1.926	1.535
1.941	1.513
2.013	1.313
1.977	1.302
2.007	1.197
1.974	1.190
2.004	1.155
1.998	1.151
2.019	1.140
2.001	1.140
1.908	1.214
1.980	1.221
1.831	1.442
1.845	1.461
1.734	1.882
1.710	1.927
1.635	2.321
1.602	2.397
1.398	3.275
1.374	3.438

Sept. 11, p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.992	1.380
2.022	1.396

2.001	1.492
1.953	1.512
1.905	1.800
1.902	1.840
1.869	2.161
1.827	2.223
1.770	2.620
1.746	2.710
1.656	3.595
1.635	3.780

Sept. 13, p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.938	1.431
1.914	1.446
1.851	1.725
1.833	1.756
1.779	2.013
1.812	2.064
1.734	2.415
1.707	2.493
1.548	3.110
1.566	3.257

Sept. 14, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
2.118	1.268
2.058	1.258
2.118	1.192
2.088	1.188
2.076	1.162
2.106	1,162
2.058	1.433
2.022	1.453
1.941	1.853
1.959	1.894
1.782	2.833
1.770	2.930

Sept. 15, p. m.
C. G. A.
II. .764

R.	Sec. Z.
2.094	1.332
2.115	1.343
2.019	1.648
2.034	1.677
1.959	1.922
1.947	1.963
1.899	2.272
1.887	2.343
1.821	2.810
1.794	2.918
1.674	3.845
1.653	4.043

Sept. 16, a. m.
C. G. A.
II. .764

R.	Sec. Z.
2.085	1.824
2.094	1.788

2.109	1.575
2.124	1.552
2.121	1.280
2.181	1.270
2.190	1.192
2.205	1.189

Sept. 19, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.764	2.648
1.788	2.558
2.001	1.682
1.989	1.653
2.043	1.479
2.043	1.461
2.106	1.240
2.097	1.232
2.106	1.192
2.091	1.191
1.905	1.386
1.884	1.401
1.854	1.552
1.869	1.576
1.824	1.833
1.827	1.872
1.779	2.354
1.761	2.424
1.650	2.990
1.620	3.110

Sept. 21, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.665	3.470
1.701	3.320
1.791	2.703
1.806	2.608
1.974	1.685
2.004	1.658
2.037	1.417
2.064	1.403
2.085	1.263
2.079	1.258
2.124	1.190
2.106	1.190
2.064	1.210
2.061	1.216
1.998	1.350
1.971	1.362

Sept. 26, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.791	2.670
1.803	2.582
1.971	1.672
1.983	1.646
2.016	1.467
2.010	1.450

2.061	1.338
2.073	1.329
2.097	1.246
2.079	1.242

Sept. 27, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.761	3.570
1.752	3.400
1.896	2.667
1.905	2.578
2.064	1.748
2.061	1.716
2.124	1.452
2.097	1.438
2.145	1.281
2.136	1.275
2.139	1.230
2.157	1.230
2.100	1.341
2.100	1.351
2.076	1.479
2.079	1.498
2.025	1.738
2.007	1.772
1.956	2.050
1.950	2.100
1.887	2.510
1.878	2.598
1.752	3.328
1.689	3.485

Oct. 3, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.791	2.930
1.815	2.823
2.034	1.672
2.022	1.650
2.073	1.439
2.067	1.427
2.100	1.320
2.091	1.315
2.094	1.279
2.100	1.277

Oct. 4, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.635	3.695
1.674	3.575
1.803	2.770
1.782	2.680
2.013	1.678
1.989	1.651
2.004	1.468
2.025	1.452
2.013	1.353
2.037	1.348

1.932	1.600
1.938	1.622
1.917	1.839
1.908	1.872
1.842	2.182
1.809	2.235
1.752	2.702
1.743	2.793
1.611	3.655
1.596	3.820

Oct. 6, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.767	3.666
1.779	3.500
1.914	2.778
1.884	2.686
2.091	1.700
2.106	1.672
2.100	1.512
2.130	1.492
2.130	1.402
2.139	1.392
2.175	1.316
2.178	1.312
2.151	1.290
2.187	1.291

Oct. 10, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.692	4.000
1.719	3.810
1.836	2.945
1.848	2.850
2.043	1.792
2.046	1.763
2.070	1.601
2.076	1.582
2.136	1.423
2.106	1.413
2.124	1.340
2.124	1.335
2.103	1.324
2.121	1.328
2.073	1.369
2.067	1.378
1.971	1.419
1.932	1.429

Oct. 12, p. m.
C. G. A.
II. .764

R.	Sec. Z.
2.049	1.350
2.064	1.352
2.031	1.402
2.034	1.412
1.953	1.687
1.956	1.712
1.881	1.956

1.872	2.003
1.818	2.330
1.782	2.385
1.665	2.980
1.677	3.100
1.497	4.050
1.485	4.350

Oct. 18, a. m. and p. m.
C. G. A.
II. .764

R.	Sec. Z.
1.758	3.860
1.800	3.690
1.917	2.785
1.944	2.698
2.124	1.879
2.088	1.848
2.103	1.706
2.133	1.683
2.148	1.563
2.130	1.549
2.196	1.430
2.211	1.423
2.190	1.390
2.151	1.389
2.142	1.389
2.142	1.390
2.010	1.748
2.022	1.775
1.941	2.053
1.923	2.100
1.866	2.420
1.869	2.475
1.764	3.040
1.788	3.175
1.635	4.125
1.614	4.390

Oct. 20, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.626	(4.7?)
1.653	(4.35?)
1.827	3.325
1.812	3.200
2.052	1.883
2.067	1.850
2.109	1.656
2.106	1.638
2.145	1.497
2.118	1.483
2.157	1.435
2.139	1.430
2.163	1.403
2.139	1.402

Oct. 24, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.719	3.600
1.746	3.465

1.998	2.110
2.013	2.070
2.031	1.840
2.037	1.813
2.097	1.582
2.082	1.570
2.097	1.467
2.136	1.460
2.124	1.440
2.133	1.440

Oct. 25, p. m.
C. G. A.
II. .764

R.	Sec. Z.
2.022	1.719
1.995	1.741
1.911	1.891
1.893	1.922
1.761	2.223
1.743	2.277
1.674	2.713
1.674	2.788
1.620	3.480
1.632	3.640

Oct. 26, p. m.
C. G. A.
II. .764

R.	Sec. Z.
2.103	1.557
2.091	1.569
2.013	1.827
1.995	1.852
1.926	2.121
1.920	2.171
1.869	2.527
1.830	2.588
1.746	3.122
1.707	3.247

1906.
May 13, a m.
C. G. A.
II. .764

R.	Sec. Z.
1.605	2.521
1.647	2.447
1.728	2.022
1.728	1.972
1.962	1.426
1.929	1.406
1.950	1.297
1.932	1.282
1.959	1.190
1.953	1.181
1.992	1.110
2.016	1.105
1.977	1.066
1.983	1.061

May 16, a. m. and p. m.
C. G. A.
III. .764

R.	Sec. Z.
2.112	1.125
2.094	1.118

II.

2.136	1.092
2.166	1.086
2.058	1.211
2.034	1.230
2.031	1.320
2.016	1.338
1.974	1.472
1.956	1.494
1.911	1.729
1.899	1.763
1.788	2.048
1.779	2.102
1.707	2.550
1.680	2.640

May 17, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.743	2.670
1.776	2.585
1.848	2.150
1.869	2.093
1.974	1.428
1.992	1.408
1.998?	1.278
2.058	1.263
2.070	1.147
2.064	1.137
2.073	1.083
2.103	1.078
2.091	1.043
2.097	1.042
2.109	1.035
2.091	1.035

May 18, p. m.
C. G. A.
II. .764

R.	Sec. Z.
2.046	1.203
2.040	1.216
2.010	1.332
1.989	1.340
1.908	1.502
1.899	1.528
1.896	1.763
1.890	1.803
1.812	2.117
1.794	2.177
1.695	2.595

May 19, a. m.
C. G. A.
II. .764

R.	Sec. Z.
1.842	2.298
1.812	2.230
1.935	1.921
1.944	1.877
2.025	1.440
2.025	1.419
2.115	1.280
2.061	1.266

Table 13.—*Pyrheliometer readings*—Continued.

MOUNT WILSON, CALIFORNIA.

[Elevation, 1,780 meters.]

2.097	1.170
2.106	1.161
2.106	1.105
2.118	1.099
2.112	1.065
2.151	1.060

May 29, a. m.
C. G. A.
H. K. P.
II. .764

R.	Sec. Z.
1.683	3.727
1.716	3.555
1.785	2.933
1.821	2.827
1.929	2.460
1.914	2.380
1.917	2.142
1.980	2.086
2.001	1.889
2.094	1.527
2.130	1.502
2.100	1.383
2.133	1.367
2.106	1.261
2.082	1.247
2.184	1.202
2.115	1.191

May 30, a. m.
H. K. P.
II. .764

R.	Sec. Z.
1.602	3.920
1.620	3.740
1.758	3.120
1.740	2.990
1.812	2.583
1.833	2.497
1.863	2.210
1.953	1.948
1.992	1.903
2.064	1.478
2.019	1.456
2.049	1.335
2.067	1.318
2.010	1.227
2.055	1.195
2.034	1.090
2.085	1.085

May 31, a. m.
H. K. P.
II. .764

R.	Sec. Z.
1.587	3.700
1.656	3.110
1.653	2.985
1.770	2.572
1.749	2.495
1.830	2.210
1.839	2.150
1.848	1.942
1.887	1.898
2.001	1.500
2.040	1.475

1.998	1.336
2.028	1.318
2.055	1.216
2.085	1.204
2.061	1.146
2.073	1.138
2.112	1.092
2.100	1.086
2.109	1.052
2.070	1.050

June 6, a. m.
H. K. P.
II. .764

R.	Sec. Z.
1.587	3.835
1.617	3.660
1.710	3.060
1.719	2.932
1.791	2.558
1.785	2.470
1.854	2.193
1.860	2.134
1.890	1.932
1.887	1.889
1.989	1.510
1.986	1.489
2.007	1.402
2.052	1.383
2.007	1.276
1.995	1.263
2.133	1.183
2.106	1.172
2.046	1.113
2.121	1.107

June 7, a. m.
H. K. P.
II. .764

R.	Sec. Z.
1.695	3.790
1.662	3.610
1.788	3.062
1.812	2.932
1.854	2.578
1.875	2.490
1.935	2.208
1.941	2.149
1.989	1.943
1.992	1.900
2.088?	1.517
2.052	1.493
2.070	1.412
2.076	1.389
2.079	1.279
2.079	1.266
2.127	1.173
2.151	1.162
2.121	1.103
2.139	1.098

June 9, a. m.
H. K. P.
II. .764

R.	Sec. Z.
1.593	3.738
1.617	3.562

1.671	3.043
1.713	2.926
1.746	2.563
1.776	2.478
1.824	2.203
1.824	2.147
1.881	1.939
1.902	1.893
1.914	1.486
2.016	1.463
2.082	1.336
2.037	1.319
2.043	1.217
2.037	1.207
2.019	1.144
2.076	1.136
2.034	1.091
2.061	1.086
2.052	1.048
2.055	1.045

June 12, a. m.
and p. m.
H. K. P.
II. .764

R.	Sec. Z.
1.506	3.665
1.536	3.510
1.635	3.010
1.674	2.900
1.758	2.555
1.743	2.472
1.830	2.200
1.854	2.144
1.881	1.934
1.890	1.890
2.022	1.081
2.073	1.087
2.076	1.132
2.031	1.140
2.052	1.203
2.031	1.218
2.019	1.308
2.031	1.323
1.995	1.448
1.971	1.470
1.944	1.640
1.920	1.673
1.890	1.870
1.878	1.912
1.830	2.117
1.797	2.172
1.767	2.432
1.710	2.512

June 15, a. m.
H. K. P.
II. .764

R.	Sec. Z.
1.752	3.240
1.740	3.112
1.806	2.679
1.812	2.587
1.872	2.281
1.887	2.222
1.908	2.003

1.932	1.953
2.016	1.517
2.043	1.493
2.034	1.406
2.061	1.386
2.073	1.276
2.103	1.260
2.103	1.182
2.091	1.172
2.130	1.117
2.100	1.109
2.172	1.070
2.103	1.068
2.106	1.040
2.055	1.039
2.169	1.021
2.139	1.021

June 16, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.305	3.640
1.333	3.465

II. .764

1.653	3.020
1.662	2.900
1.701	2.567
1.734	2.489
1.785	2.222
1.797	2.163
1.839	1.967
1.851	1.921
1.956	1.476
1.947	1.452
1.989	1.359
2.028	1.340
2.040	1.243
2.082	1.231
2.073	1.163
2.073	1.153
2.139	1.106
2.100	1.100

June 19, a. m.
L. R. I.
II. .764

R.	Sec. Z.
1.593	3.672
1.623	3.500
1.737	2.925
1.749	2.807
1.809	2.298
1.854	2.233
1.881	2.012
1.896	1.963
1.992	1.498
2.049	1.477
2.040	1.329
2.046	1.311
2.055	1.213
2.052	1.202
2.055	1.110
2.064	1.103
2.079	1.063

2.052	1.060
2.085	1.032
2.088	1.031
2.097	1.030
2.070	1.020
2.067	1.020

June 20, a. m.
L. R. I.
IV. .902

R	Sec. Z.
1.584	2.462
1.570	2.382
1.625	2,160
1.656	2.102
1.673	1.950
1.663	1.902
1.735	1.518
1.764	1.492
1.769	1.350
1.764	1.333
1.805	1.171
1.831	1.162
1.816	1.119
1.819	1.111
1.822	1.037
1.817	1.033

June 22, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.564	2.579
1.565	2.503
1.607	2.268
1.634	2.203
1.656	2.010
1.679	1.961
1.733	1.548
1.743	1.523
1.779	1.349
1.765	1.333
1.794	1.225
1.792	1.213
1.831	1.092
1.835	1.087
1.840	1.025
1.807	1.025

June 23, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.439	2.952
1.454	2.832
1.500	2.560
1.486	2.480
1.519	2.266
1.555	2.203
1.582	2.022
1.587	1.973
1.695	1.512
1.675	1.487
1.699	1.363
1.720	1.345
1.751	1.207

1.737	1.196
1.764	1.133
1.767	1.126

June 29, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.411	3.282
1.426	3.143
1.486	2.849
1.506	2.742
1.553	2.371
1.556	2.300
1.598	2.040
1.607	1.987
1.692	1.536
1.701	1.512
1.737	1.364
1.744	1.345
1.774	1.218
1.763	1.207
1.781	1.095
1.782	1.090

June 30, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.392	3.150
1.408	3.029
1.482	2.570
1.483	2.486
1.521	2.268
1.542	2.204
1.575	2.028
1.582	1.979
1.665	1.562
1.671	1.537
1.719	1.350
1.711	1.331
1.738	1.216
1.736	1.203
1.780	1.101
1.769	1.095

July 3, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.354	2.910
1.352	2.805
1.423	2.426
1.457	2.354
1.527	2.065
1.528	2.015
1.627	1.550
1.610	1.523
1.656	1.358
1.665	1.339
1.703	1.205
1.709	1.194
1.730	1.097
1.704	1.092

July 6, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.237	3.350
1.266	3.200
1.334	2.773
1.347	2.682
1.415	2.283
1.418	2.220
1.472	1.990
1.472	1.941
1.585	1.528
1.574	1.503
1.610	1.372
1.622	1.356
1.651	1.201
1.652	1.190
1.670	1.077
1.675	1.069

July 10, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.253	3.098
1.268	2.975
1.337	2.618
1.340	2.537
1.388	2.256
1.413	2.193
1.438	2.032
1.446	1.977
1.530	1.553
1.518	1.528
1.559	1.388
1.576	1.369
1.594	1.238
1.607	1.224
1.636	1.171
1.652	1.161
1.663	1.111
1.656	1.106
1.655	1.081
1.658	1.077

July 11, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.159	3.279
1.183	3.138
1.290	2.667
1.318	2.575
1.376	2.240
1.401	2.177
1.422	2.052
1.413	2.006
1.535	1.584
1.533	1.556
1.598	1.356
1.600	1.335
1.609	1.252
1.603	1.240
1.633	1.106
1.646	1.099

July 17, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.264	3.880
1.292	3.684
1.335	3.282
1.361	3.144
1.435	2.673
1.457	2.585
1.522	2.309
1.500	2.243
1.543	2.017
1.554	1.970
1.635	1.607
1.643	1.578
1.682	1.320
1.673	1.303
1.713	1.164
1.726	1.156

July 18, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.354	3.270
1.375	3.130
1.448	2.707
1.473	2.614
1.525	2.145
1.543	2.089
1.628	1.636
1.609	1.605
1.633	1.506
1.640	1.481
1.712	1.257
1.679	1.243
1.725	1.157
1.717	1.148

July 21, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.236	3.035
1.247	2.915
1.338	2.513
1.336	2.432
1.406	2.107
1.420	2.053
1.520	1.639
1.529	1.611
1.595	1.387
1.589	1.369
1.635	1.164
1.623	1.155

July 24, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.186	3.372
1.198	3.223
1.280	2.724
1.138	2.630
1.369	2.202

Table 13.—*Pyrheliometer readings*—Continued.

MOUNT WILSON, CALIFORNIA.

[Elevation, 1,780 meters.]

1.376	2.143
1.444	1.674
1.439	1.642

July 27, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.363	3.107
1.393	2.984
1.427	2.645
1.446	2.554
1.480	2.326
1.491	2.258
1.514	2.133
1.518	2.077
1.602	1.637
1.607	1.606
1.646	1.434
1.643	1.414
1.709	1.280
1.672	1.266
1.669	1.227
1.688	1.217
1.693	1.159
1.679	1.150

July 28, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.345	3.194
1.350	3.063
1.412	2.674
1.434	2.590
1.483	2.303
1.503	2.238
1.528	2.085
1.526	2.036
1.603	1.664
1.606	1.633
1.689	1.357
1.673	1.341
1.701	1.220
1.713	1.207
1.730	1.122
1.736	1.114

July 31, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.471	3.262
1.474	3.125
1.511	2.802
1.542	2.700
1.572	2.457
1.582	2.385
1.633	2.155
1.640	2.095
1.726	1.658
1.736	1.626
1.767	1.415

1.782	1.392
1.816	1.213
1.829	1.203
1.867	1.075
1.855	1.070

Aug. 1, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.479	3.315
1.491	3.170
1.525	2.860
1.559	2.760
1.576	2.539
1.602	2.460
1.644	2.177
1.654	2.117
1.717	1.678
1.734	1.644
1.786	1.317
1.808	1.301
1.832	1.138
1.840	1.130

Aug. 3, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.429	3.592
1.444	3.423
1.492	2.932
1.514	2.824
1.579	2.395
1.588	2.320
1.609	2.141
1.631	2.080
1.690	1.618
1.718	1.590
1.757	1.429
1.719	1.409
1.763	1.203
1.760	1.191
1.788	1.113
1.795	1.10[illegible]

Aug. 4, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.419	3.280
1.439	3.142
1.479	2.766
1.527	2.668
1.556	2.430
1.566	2.356
1.585	2.146
1.589	2.084
1.659	1.648
1.650	1.622
1.719	1.378
1.712	1.360
1.742	1.241
1.765	1.229
1.784	1.153
1.770	1.143

Aug. 7, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.498	2.929
1.501	2.827
1.565	2.500
1.578	2.423
1.594	2.223
1.608	2.165
1.693	1.768
1.700	1.733
1.729	1.458
1.736	1.437
1.800	1.216
1.793	1.208
1.807	1.100
1.802	1.096
1.822	1.067
1.811	1.063

Aug. 8, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.495	3.236
1.504	3.089
1.556	2.700
1.579	2.609
1.641	2.200
1.641	2.140
1.729	1.670
1.724	1.640
1.742	1.490
1.746	1.469
1.758	1.340
1.768	1.323
1.767	1.240
1.793	1.228
1.825	1.116
1.824	1.109
1.826	1.054
1.826	1.054

Aug. 14, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.256	3.258
1.265	3.127
1.322	2.822
1.347	2.722
1.449	2.302
1.437	2.237
1.542	1.688
1.560	1.653
1.624	1.429
1.606	1.408
1.651	1.292
1.652	1.277
1.671	1.182
1.702	1.173
1.675	1.133

Aug. 15, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.203	3.358
1.234	3.214
1.277	2.840
1.304	2.735
1.356	2.540
1.369	2.450
1.396	2.262
1.408	2.199
1.542	1.533
1.555	1.508
1.577	1.368
1.572	1.352

Aug. 17, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.232	3.360
1.270	3.230
1.317	2.729
1.354	2.636
1.403	2.350
1.412	2.276
1.533	1.694
1.532	1.664

Aug. 21, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.262	4.510
1.289	4.200
1.408	3.605
1.449	3.452
1.548	2.920
1.560	2.811
1.609	2.402
1.633	2.334
1.720	1.780
1.730	1.743
1.789	1.577
1.799	1.549
1.864	1.298
1.860	1.283
1.860	1.249
1.860	1.237
1.862	1.182
1.862	1.174

Aug. 23, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.467	3.855
1.506	3.677
1.556	3.135
1.580	3.010
1.603	2.728

1.609	2.631
1.653	2.423
1.660	2.351
1.754	1.806
1.757	1.770
1.793	1.608
1.794	1.580
1.847	1.310
1.852	1.295
1.835	1.154
1.849	1.147

Aug. 25, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.342	3.945
1.372	3.770
1.411	3.314
1.442	3.174
1.476	2.839
1.504	2.732
1.531	2.452
1.561	2.378
1.647	1.827
1.650	1.788
1.734	1.492
1.723	1.472
1.766	1.234
1.784	1.223
1.807	1.173
1.804	1.165

Aug. 29, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.189	2.854
1.225	2.748
1.238	2.581
1.276	2.493
1.418	1.796
1.414	1.760
1.509	1.453
1.511	1.433

Aug. 31, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.266	3.391
1.282	3.249
1.343	2.905
1.356	2.797
1.405	2.507
1.411	2.427
1.537	1.841
1.562	1.715
1.569	1.684
1.625	1.462
1.611	1.442
1.638	1.283

1.658	1.270
1.649	1.257
1.671	1.184
1.660	1.176
1.670	1.168
1.719	1.109
1.699	1.110
1.680	1.110

Sept. 1, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.419	3.050
1.432	2.933
1.482	2.638
1.514	2.548
1.647	1.894
1.662	1.853
1.719	1.592
1.729	1.526
1.729	1.502
1.788	1.314
1.742	1.299
1.764	1.186
1.776	1.178
1.722	1.115
1.767	1.114

Sept. 4, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.358	3.800
1.368	3.630
1.447	3.086
1.489	2.708
1.514	2.610
1.662	1.240
1.624	1.230

Sept. 5, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.364	3.700
1.404	3.500
1.474	2.960
1.473	2.845
1.515	2.635
1.532	2.539
1.644	1.885
1.659	1.845
1.681	1.608
1.701	1.580
1.756	1.334
1.744	1.322
1.742	1.194
1.751	1.186
1.768	1.143
1.785	1.140

Sept. 8, a. m.
L. R. I.
IV. .902

R.	Sec. Z.
1.331	3.836
1.350	3.650
1.429	3.059
1.435	2.945
1.476	2.683
1.498	2.589

Sept. 9, a. m.
L. R. I., C. G. A.
IV. .902

R.	Sec. Z.
1.302	4.715
1.333	4.425
1.389	3.735
1.416	3.560
1.503	2.949
1.508	2.836
1.606	2.162
1.629	2.105
1.718	1.659
1.727	1.630
1.770	1.395
1.762	1.379
1.853	1.149
1.824	1.145
1.817	1.141
1.812	1.143

Sept. 11, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.482	3.632
1.578	2.820
1.708	2.011
1.768	1.750
1.768	1.715
1.813	1.528
1.811	1.504
1.834	1.365
1.842	1.350
1.852	1.264
1.806	1.254
1.817	1.160

Sept. 18, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.451	3.790
1.574	2.965
1.754	1.794
1.746	1.758
1.796	1.541
1.783	1.520
1.822	1.380
1.817	1.367
1.811	1.267
1.821	1.259
1.843	1.193
1.849	1.190

1906.
Sept. 20, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.297	3.960
1.409	3.100
1.627	1.900
1.631	1.860
1.687	1.630
1.688	1.602
1.712	1.428
1.708	1.412
1.719	1.298
1.720	1.288
1.728	1.210
1.740	1.207

Sept. 25, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.353	3.760
1.446	3.096
1.635	1.926
1.618	1.884
1.687	1.646
1.699	1.620
1.742	1.464
1.724	1.448
1.753	1.316
1.755	1.308
1.758	1.242
1.766	1.238

Sept. 28, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.296	4.430
1.442	3.080
1.650	1.883
1.644	1.848
1.684	1.656
1.697	1.630
1.755	1.460
1.733	1.443
1.764	1.337
1.780	1.327
1.776	1.281
1.797	1.277
1.788	1.237
1.819	1.234

Oct. 2, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.369	3.430
1.622	1.922
1.598	1.885
1.658	1.642
1.686	1.620
1.739	1.410

Table 13.—*Pyrheliometer readings*—Continued.

MT. WILSON.

[Elevation, 1,780 meters.]

1.750	1.400
1.774	1.307
1.776	1.300
1.750	1.268
1.748	1.265

Oct. 4, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.219	(4.75?)
1.377	3.665
1.417	3.500
1.645	1.988
1.674	1.948
1.698	1.727
1.708	1.699
1.754	1.530
1.756	1.513
1.750	1.403

1.754	1.395
1.790	1.338
1.772	1.330

Oct. 6, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.451	3.800
1.482	3.623
1.718	2.048
1.737	2.003
1.758	1.672
1.768	1.648
1.811	1.483
1.804	1.468
1.812	1.376
1.814	1.368
1.810	1.310
1.825	1.306

Oct. 9, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.436	3.815
1.470	3.650
1.684	2.102
1.700	2.055
1.738	1.802
1.743	1.772
1.776	1.617
1.789	1.597
1.799	1.482
1.803	1.468
1.819	1.383
1.825	1.375
1.783	1.330
1.796	1.329

Oct. 11, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.359	4.045
1.390	3.830
1.630	2.187
1.641	2.136
1.687	1.880
1.686	1.845
1.714	1.680
1.715	1.657
1.731	1.512
1.742	1.495
1.769	1.407
1.767	1.399
1.772	1.348
1.769	1.343

Oct. 13, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.349	4.080
1.393	3.870
1.609	2.197
1.627	2.144
1.705	1.863
1.748	1.832
1.739	1.672
1.720	1.648
1.747	1.502
1.743	1.484
1.767	1.403
1.756	1.397

Oct. 16, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.471	(4.450)
1.486	4.150
1.745	2.160
1.773	2.112
1.790	1.829
1.809	1.797
1.832	1.640
1.829	1.620
1.858	1.500
1.863	1.486
1.880	1.422
1.870	1.418

Oct. 18, a. m.
J. E., C. G. A.
IV. .902

R.	Sec. Z.
1.400	(4.80)
1.591	2.542
1.629	2.473
1.714	1.840
1.724	1.810
1.759	1.580
1.751	1.564
1.775	1.478
1.767	1.468
1.802	1.400
1.801	1.395

Oct. 20, a. m.
C. G. A.
IV. .902

R.	Sec. Z.
1.481	4.30
1.506	4.040
1.735	2.253
1.727	2.203
1.769	1.913
1.812	1.880
1.805	1.698
1.814	1.676
1.831	1.570
1.820	1.554

Oct. 23, a. m.
C. M. O.
IV. .902

R.	Sec. Z.
1.268	(5.5?)
1.317	(5.10)
1.430	(4.35)
1.443	(4.10)
1.499	3.63
1.504	3.50
1.712	2.290
1.689	2.239
1.750	2.018
1.733	1.977
1.748	1.758
1.782	1.733
1.826	1.610
1.830	1.596
1.809	1.512
1.809	1.502
1.824	1.453
1.821	1.448

WASHINGTON, D. C.

[Elevation, 10 meters.]

1902.

Oct. 9, a. m. and p. m.
J. R. B.
Crova. .4096

R.	Sec. Z.
3.006	1.580
3.396	1.418
3.288	1.510
3.027	1.785
2.910	2.040
2.688	2.565
2.232	3.260

Oct. 15, a. m. and p. m.
J. R. B.
Crova. .4096

R.	Sec. Z.
3.504	1.562
3.615	1.552
3.540	1.510
3.468	1.504
3.567	1.480
3.600	1.477
3.558	1.480
3.549	1.484
3.546	1.605
3.432	1.625
3.456	1.697
3.327	1.718
3.240	1.903
3.072	1.940
2.820	2.367
2.880	2.440

Oct. 22, a. m. and p. m.
J. R. B.
Crova. .4096

R.	Sec. Z.
2.748	1.984
2.745	1.948
3.042	1.766
3.120	1.744
3.342	1.638
3.486	1.625
3.297	2.040
3.180	2.092

1903.

Feb. 19, a. m. and p. m.
C. G. A.
Crova.† .4096

R.	Sec. Z.
2.583	1.952
2.868	1.718
2.787	1.679
2.709	1.590
3.069	1.583
2.694	1.577
2.574	1.586
3.141	1.621
2.943	1.638
2.808	1.773
2.613	1.981
2.391	2.329
2.064	2.900

Mar. 25, p. m.
C. G. A.
Crova.† .4096

R.	Sec. Z.
2.538	1.358
2.289	1.369
2.739	1.413
2.772	1.427
2.685	1.460
2.490	1.733
2.295	1.819
1.890	2.270
1.794	2.443

Mar. 26, a. m. and p. m.
C. G. A.
Crova.† .4096

R.	Sec. Z.
2.490	1.628
2.547	1.603
2.538	1.532
2.754	1.255
2.787	1.272
2.748	1.282
2.730	1.397
2.661	1.409
2.634	1.440
2.463	1.638
2.421	1.720
2.061	2.268

Apr. 17, a. m. and p. m.
C. G. A.
I. .7524.

R.	Sec. Z.
1.767	1.158
1.698	1.150
1.656	1.140
1.662	1.140
1.617	1.210
1.597	1.303
1.549	1.398
1.301	1.807

Apr. 29, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.404	1.127
1.452	1.130
1.428	1.183
1.326	1.318
1.149	1.575

July 7, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.692	1.060
1.581	1.071
1.635	1.109
1.578	1.130
1.563	1.219
1.506	1.309
1.407	1.499

Aug. 24, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.452	1.148
1.472	1.188
1.428	1.242
1.347	1.466

Sept. 14, p. m.
F. E. F.
I. .7524

R.	Sec. Z.
1.512	1.462
1.323	1.472
1.656	1.619
1.671	1.632
1.470	1.900
1.140	2.596

Oct. 14, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.605	1.619
1.635	1.634
1.482	1.870
1.401	2.290
1.140	3.020

Oct. 29, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.464	1.661
1.425	1.680
1.389	1.782
1.368	1.931
1.035	2.786

Dec. 7, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.488	2.150
1.485	2.165
1.425	2.245
1.377	2.435
1.350	2.550
1.266	2.895
1.224	3.220
1.077	3.696

Crova. .4096

2.436	2.770
2.319	3.047
2.304	3.440

Dec. 23, a. m. and p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.542	2.158
1.491	2.150
1.410	2.150
1.536	2.248
1.563	2.266
1.530	2.360
1.467	2.390
1.458	2.520
1.461	2.552
1.353	2.979
1.341	3.113

1904.

Jan. 27, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.449	1.862
1.500	1.863
1.530	1.877
1.587	1.881
1.467	1.945
1.482	1.958
1.515	1.970
1.518	2.130
1.530	2.155
1.380	2.460
1.368	2.516
1.281	2.890
1.029	4.120

Feb. 11, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.596	1.676
1.674	1.687
1.470	1.790
1.391	1.990
1.320	2.352
1.128	2.938

Mar 4, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.662	1.429
1.665	1.433
1.652	1.455
1.674	1.493
1.680	1.534
1.608	1.630
1.443	1.948
1.473	1.982
1.383	2.238
1.350	2.390

Apr. 4, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.842	1.205
1.836	1.208
1.848	1.232
1.797	1.238
1.719	1.292
1.716	1.298
1.704	1.366
1.725	1.380
1.695	1.540
1.665	1.560
1.551	1.702
1.590	1.733
1.455	2.120
1.479	2.180

May 12, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.656	1.120
1.680	1.127
1.599	1.158
1.653	1.166
1.632	1.240
1.623	1.250
1.584	1.418
1.560	1.436
1.497	1.581
1.506	1.608
1.428	1.740
1.446	1.770

† On these days actinometer reads in siderostat beam.

Table 13.—*Pyrheliometer readings*—Continued.

WASHINGTON, D. C.

[Elevation, 10 meters.]

May 25, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.500	1.298
1.539	1.312
1.416	1.412
1.419	1.430
1.359	1.475
1.398	1.498
1.269	1.770
1.272	1.822

May 28, p. m.
C. G. A.
I. .7524

R.	Sec. Z.
1.797	1.100
1.791	1.107
1.711	1.142
1.722	1.150
1.743	1.200
1.728	1.212
1.617	1.282
1.509	1.297
1.629	1.390
1.623	1.410
1.569	1.572
1.563	1.600
1.434	1.843
1.467	1.888

Sept. 22, p. m.
S. A. M.
I. .7524

R.	Sec. Z.
1.814	1.426
1.691	1.438
1.685	1.452
1.821	1.531
1.732	1.548
1.635	1.568
1.637	1.709
1.689	1.734
1.700	1.762
1.552	1.874
1.620	1.909
1.604	1.948
1.436	2.147
1.434	2.200
1.373	2.253
1.439	2.456
1.444	2.530
1.284	2.608
1.221	2.803
1.297	2.904
1.264	3.008
1.203	3.470
1.238	3.630

Oct. 5, p. m.
F. E. F.
I. .7524

R.	Sec. Z.
1.551	1.462
1.617	1.472
1.566	1.483
1.524	1.574
1.560	1.590
1.524	1.608
1.452	1.764
1.443	1.793
1.386	1.822
1.325	2.055
1.284	2.104
1.224	2.155
1.096	2.616
1.104	2.695
1.095	2.780
0.917	3.710
0.894	3.890

Oct. 21, p. m.
C. G. A.,
Crova. .4096

R.	Sec. Z.
3.739	1.568
3.429	1.580
3.375	1.587
3.399	1.594
3.473	1.653
3.375	1.666
3.499	1.680
3.181	1.820
3.303	1.844
3.399	1.870
3.221	2.172
3.072	2.214
3.055	2.682
2.949	2.760
2.824	2.845
2.436	3.845
2.325	4.030

Nov. 16, p. m.
C. G. A.,
Crova. .4096

R.	Sec. Z.
2.724	2.095
2.607	2.116
2.682	2.140
2.637	2.266
2.496	2.300
2.562	2.333
2.337	2.655
2.271	2.715
2.346	2.775
1.851	3.630
1.893	3.760
1.890	3.900
1.692	4.35
1.707	4.60

1905.

Jan. 26, p. m.
C. G. A.
I. .8102

R.	Sec. Z.
1.668	1.910
1.665	1.921
1.653	1.933
1.620	2.010
1.632	2.030
1.602	2.150
1.611	2.175
1.588	2.205
1.524	2.432
1.551	2.476
1.494	2.522
1.458	2.728
1.461	2.793
1.362	3.286
1.302	3.394
1.308	3.502

Crova. .4096

3.414	1.968
3.387	1.980

Feb. 7, p. m.
C. G. A.
I. .8102

R.	Sec. Z.
1.542	1.775
1.533	1.782
1.509	1.790
1.527	1.880
1.497	1.898
1.452	1.916
1.446	2.040
1.443	2.068
1.416	2.096
1.380	2.275
1.362	2.314
1.362	2.355
1.263	2.595
1.272	2.658
1.230	2.720
1.083	3.210
1.104	3.318
1.065	3.430

Crova. .4096

3.075	1.822
3.129	1.837
3.036	1.853

Feb. 14, p. m.
C. G. A.
I. .8102

R.	Sec. Z.
1.620	1.796
1.728	1.812
1.659	1.831
1.590	1.938
1.611	1.966
1.635	2.185
1.647	2.225
1.542	2.475
1.305	3.170
1.263	3.280
1.299	3.398
1.230	3.525
1.065	4.100

Crova. .4096

3.279	2.045
3.387	2.075
3.378	2.110

Mar. 2, p. m.
C. G. A.
I. .8102

R.	Sec. Z.
1.812	1.557
1.776	1.570
1.734	1.588
1.707	1.695
1.644	1.715
1.653	1.920
1.629	1.951
1.599	1.992
1.524	2.338
1.422	2.656

Crova. .4096

3.381	1.632
3.492	1.647
3.264	1.662
3.114	2.085
3.210	2.130

May 20, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.591	1.146
1.599	1.152
1.575	1.160
1.696	1.189
1.650	1.198
1.656	1.208
1.665	1.218
1.656	1.229
1.694	1.240
1.662	1.252
1.617	1.266
1.611	1.280
1.656	1.294
1.653	1.308
1.650	1.323
1.647	1.338
1.608	1.354
1.626	1.370
1.564	1.442
1.542	1.462
1.534	1.483
1.528	1.597
1.539	1.625
1.481	1.653

June 5, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.666	1.090
1.680	1.094
1.734	1.095
1.668	1.110
1.644	1.114
1.605	1.121
1.687	1.136
1.647	1.143
1.662	1.150
1.680	1.159
1.674	1.168
1.686	1.177
1.600	1.220
1.587	1.230
1.560	1.243
1.593	1.291
1.587	1.306
1.569	1.321
1.508	1.389
1.539	1.406
1.503	1.423
1.502	1.510
1.470	1.532
1.422	1.558
1.388	1.687
1.452	1.718
1.402	1.751
1.248	1.785
1.335	1.820
1.313	2.000
1.311	2.042
1.227	2.087
1.176	2.135
1.212	2.185

F. E. F.,
Crova. .4096

3.360	1.136
3.165	1.152
3.159	1.162
3.219	1.170

June 22, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.608	1.100
1.605	1.106
1.593	1.172
1.593	1.180
1.572	1.192
1.530	1.332
1.488	1.350
1.467	1.367
1.396	1.520
1.415	1.545
1.404	1.570
1.302	1.870
1.245	1.915
1.263	1.960

II. .7460

1.713	1.123
1.683	1.131
1.683	1.139
1.593	1.212
1.656	1.221
1.620	1.234
1.656	1.247
1.629	1.260
1.632	1.272
1.596	1.407
1.596	1.427
1.590	1.445
1.356	1.675
1.454	1.705
1.446	1.740

June 27, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.680	1.105
1.680	1.111
1.662	1.118
1.569	1.275
1.566	1.288
1.554	1.304
1.494	1.472
1.461	1.494
1.434	1.518

II. .7460

1.722	1.132
1.704	1.142
1.688	1.150
1.626	1.363
1.606	1.379
1.642	1.395
1.489	1.558
1.454	1.665
1.455	1.730
1.401	1.764

Sept. 19, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.482	1.305
1.563	1.311
1.584	1.319
1.554	1.370
1.521	1.380
1.557	1.391
1.569	1.433
1.512	1.448
1.551	1.462
1.536	1.522
1.545	1.540
1.536	1.559
1.485	1.646
1.470	1.671
1.473	1.697
1.449	1.797
1.454	1.830
1.368	1.862
1.371	2.016
1.392	2.063
1.299	2.258
1.329	2.320
1.260	2.380
1.284	2.556
1.266	2.636
1.239	2.726

Sept. 26, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.782	1.328
1.770	1.333
1.755	1.340
1.770	1.362
1.758	1.370
1.779	1.379
1.782	1.387
1.710	1.568
1.668	1.587
1.662	1.609
1.644	1.683
1.641	1.710
1.560	1.821
1.542	1.852
1.584	1.883
1.584	2.050
1.548	2.098
1.506	2.144
1.425	2.292
1.422	2.350
1.488	2.413
1.344	2.678
1.365	2.772
1.296	2.868
1.260	3.270
1.215	3.400
1.176	3.538

Oct. 4, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.401	1.600
1.410	1.622
1.401	1.641
1.380	1.713
1.392	1.740
1.419	1.762
1.287	1.912
1.341	1.950
1.341	1.983
1.272	2.160
1.275	2.210
1.260	2.262
1.209	2.458
1.200	2.525
1.164	2.605
1.050	2.960
1.059	3.060
0.990	3.178
0.948	3.300
0.927	3.430

Nov. 1, p. m.
H. H. K.
I. .8102

R.	Sec. Z.
1.515	1.867
1.497	1.887
1.491	1.908
1.530	2.008
1.512	2.033
1.530	2.062
1.386	2.190
1.374	2.229
1.386	2.271
1.377	2.316
1.353	2.362
1.317	2.411
1.278	2.607
1.278	2.670
1.272	2.745
1.251	2.820
1.269	2.898
1.257	2.978
1.155	3.420
1.128	3.560
1.116	3.700
1.083	3.850
1.056	4.020
1.017	4.240

Dec. 4, p. m.
C. G. A.
I. .8102

R.	Sec. Z.
1.359	2.263
1.365	2.281
1.332	2.306
1.302	2.420
1.299	2.456
1.305	2.490
1.275	2.630
1.242	2.678
1.272	2.722
1.101	3.143
1.110	3.223
1.053	3.312
0.987	3.772
0.951	3.903
0.942	4.058

1906.

Jan. 9, p. m.
C. G. A.
I. .8102

R.	Sec. Z.
1.722	2.149
1.728	2.163
1.701	2.179
1.728	2.279
1,728	2,300
1.731	2.326
1.692	2.500
1.668	2.540
1.650	2.580
1.512	3.080
1.482	3.163
1.452	3.246
1.311	3.740
1.293	3.870

Feb. 15, p. m.
C. G. A.
I. 8102

R.	Sec. Z.
1.842	1.678
1.869	1.869

TABLE 13.—*Pyrheliometer readings*—Continued.

WASHINGTON, D. C.

[Elevation, 10 meters.]

R.	Sec. Z.
1.848	1.700
1.788	1.759
1.794	1.776
1.800	1.793
1.740	1.912
1.725	1.934
1.698	1.960
1.695	2.086
1.662	2.120
1.635	2.157
1.602	2.321
1.599	2.370
1.635	2.421
1.512	2.693
1.476	2.763
1.449	2.836

May 24, p. m.
F. E. F.
I. .8102

R.	Sec. Z.
1.449	1.201
1.464	1.212
1.497	1.223
1.422	1.268
1.446	1.280
1.404	1.293
1.401	1.353
1.413	1.371
1.389	1.389
1.350	1.458
1.311	1.480
1.347	1.502
1.266	1.595
1.200	1.623
1.224	1.652
1 194	1.730
1.245	1.763
1.197	1.800
1.122	1.900
1.107	1.940
1.077	1.990

May 29, p. m.
F. E. F.
I. .8102

R.	Sec. Z.
1.842	1.129
1.824	1.135
1.800	1.142
1.743	1.175
1.812	1.182
1.836	1.190
1.815	1.223
1.782	1.233
1.818	1.245
1.806	1.282
1.764	1.297
1.749	1.312
1.731	1.365
1.743	1.382
1.752	1.402
1.683	1.469
1.686	1.489
1.710	1.513
1.683	1.612
1.647	1.642
1.629	1.672
1.470	2.038
1.551	2.089
1.515	2.138
1.416	2.197

Oct. 8, p. m.
F. E. F.
I. .8102

R.	Sec. Z.
1.671	1.632
1.635	1.650
1.611	1.670
1.626	1.690
1.485	1.865
1.485	1.897
1.512	1.930
1.407	2.135
1.413	2.182
1.344	2.230
1.308	2.555
1.263	2.630
1.257	2.718
1.047	3.450
1.071	3.610
0 996	3.780

Nov. 6, p. m.
F. E. F.
I. .8102

R.	Sec. Z.
1.668	1.915
1.647	1.935
1.731	1.956
1.662	2.032
1.680	2.060
1.644	2.087
1.533	2.188
1.569	2.225
1.536	2.262
1.488	2.422
1.506	2.472
1.488	2.523
1.392	2.820
1.425	2.891
1.368	2.970
1.269	3.350
1.299	3.465
1.203	3.595
1.275	3.735

Nov. 22, p. m.
C. G. A.
V. .8479

R.	Sec. Z.
1.643	2.131
1.635	2.152
1.611	2.174
1.555	2.256
1.593	2.310
1.571	2.343
1.582	2.377
1.566	2.413
1.530	2.563
1.558	2.613
1.546	2.665
1.481	2.913
1.518	2.986
1.508	3.061
1.375	3.435
1.385	3.550
1.372	3.670
1.305	3.990
1.267	4.150

Dec. 26, p. m.
C. G. A.
V. .8479

R.	Sec. Z.
1.516	2.455
1.482	2.484
1.478	2.515
1.388	2.710
1.382	2.760
1.405	2.810
1.336	3.115
1.315	3.200
1.302	3.283
1.118	3.910
1.111	4.045
1.088	4.205

1907.

Feb. 15, p. m.
C. G. A.
V. .8479

R.	Sec. Z.
1.751	1.690
1.772	1.700
1.751	1.712
1.729	1.781
1.720	1.799
1.736	1.818
1.694	1.949
1.693	1.976
1.699	2.003
1.647	2.137
1.649	2.171
1.662	2.211
1.629	2.404
1.617	2.460
1.574	2.519
1.517	2.814
1.519	2.897
1.494	2.990

May 13, p. m.
C. G. A.
V. .8479

R.	Sec. Z.
1.556	1.213
1.571	1.224
1.554	1.235
1.489	1.277
1.532	1.290
1.515	1.302
1.449	1.369
1.435	1.386
1.411	1.402
1.383	1.639
1.402	1.668
1.363	1.730
1.318	1.823
1.311	1.862
1.300	1.903
1.311	1.943
1.234	2.080
1.215	2.133

May 14, p. m.
C. G. A.
V. .8479

R.	Sec. Z.
1.447	1.220
1.468	1.230
1.464	1.240
1.440	1.282
1.426	1.296
1.433	1.310
1.416	1.372
1.408	1.390
1.366	1.481
1.360	1.504
1.344	1.529
1.296	1.623
1.274	1.653
1.239	1.683
1.246	1.798
1.217	1.833
1.173	1.871
1.183	2.011
1.147	2.056

While the work of many observers shows both by observation and theory that the exponential formula $A=A_0a^{sec. z}$ does not and ought not to exactly represent pyrheliometric observations of the variation of the total intensity of solar radiation with varying altitudes of the sun, for the reason that the rays of different wave-lengths are unequally transmitted by the atmosphere, still for values of sec. z lying between 1.1 and 3.0 the deviation from the exponential law is so slight that this law offers a good means of representing approximately the principal results of a given day of observation. The most convenient mode of selecting the values of A_0 and a best adapted to represent a series of observations, consists in plotting logarithms of the observed intensity of radiation as ordinates, with values of sec. z as abscissæ, choosing the most representative straight line, and then finding the value of the intercept on the axis of ordinates, and the tangent of inclination of the line, which are the values of $\log A_0$ and $\log a$, respectively. As shown by Langley, this method applied to pyrheliometry alone must always yield a value A_0 less than the true decrease of intensity of the direct beam in transmission vertically through the atmosphere. The formula $A=A_0a^{sec. z}$ applies strictly only for homogeneous rays.

Values of A_0 and a thus obtained and approximately representative of the pyrheliometry alone will be included in Table 14 of "solar-constant" results to be given. Such values A_0, like the values of the "solar constant" given in the same table, are reduced to mean solar distance, and a symbol is given also of the degree of apparent uniformity of the transparency of the sky as indicated by the logarithmic plots just mentioned. The rating employed is as follows: Highest excellence = e^2; excellent = e; very good = v g; good = g; poor = p. This rating depends principally upon the closeness of the observed values to those which would correspond to the formula $A_0 = A\,a^{\sec. z}$ for values of z less than 3.0. The same system of rating is employed for the bolographic work, and in that connection would indicate the closeness with which the logarithmic plots of transmission for different wave-lengths approximate to the representative straight lines.

DETERMINATIONS OF THE "SOLAR CONSTANT" OF RADIATION BY THE METHOD OF HIGH AND LOW SUN OBSERVATIONS OF HOMOGENEOUS RAYS, AND THE ATMOSPHERIC TRANSMISSION FOR DIFFERENT WAVE-LENGTHS.

We now give in condensed form the results of 165 independent determinations of the "solar constant" of radiation by the spectrobolometric method. They were obtained for the most part at Mount Wilson in California, at latitude 34° 13′ 26″ north, longitude 118° 3′ 40″ west, elevation about 1,780 meters; but a considerable number were obtained from observations at Washington, latitude 38° 53′ 17″.3 north, longitude 77° 01′ 33″.6 west, elevation 10 meters. The "solar-constant" results are all reached by the complex process of combining spectrum measurements by the bolometer with pyrheliometric observations, after the manner already described; and are believed to represent the actual intensity of the solar radiation at the earth's mean distance from the sun as it is in space, and not affected by absorption or scattering within the earth's atmosphere. All the determinations of radiation are expressed approximately in calories per square centimeter per minute; but it is believed that the unit of the scale is not exactly the calorie, and that the values here given would be from 1 to 2 per cent smaller if expressed in true calories. When conclusive evidence on this point is obtained, the proper correction, if any, may be applied.

The significance of columns 3, 4, 5, and 6 of Table 14 has already been explained. Columns 7–16 give the coefficients of vertical transmission of rays of different wave-lengths in the atmosphere. Column 17 gives the "solar constant" of radiation determined by combining actinometry and bolometry. The values are reduced to mean solar distance. Columns 19 and 20 will be further explained in Chapter VI.

Table 14.—*Results of "solar-constant" measurements—Mount Wilson observations.*

Date.	a. m. or p. m.	Pressure water vapor.	Actinometry.			Bolometry.	Atmospheric transmission for different wave-lengths.										"Solar constant." E_o	Ratio. $\frac{E_o}{A_o}$	Atmospheric transmission. $\frac{A_o a}{E_o}$
			Grade.	Apparent atmospheric transmission. a.	Apparent "solar constant." A_o.	Grade.	μ 0.40	μ 0.45	μ 0.50	μ 0.60	μ 0.70	μ 0.80	μ 0.90	μ 1.00	μ 1.20	μ 1.60			
1905.		*mm.*																	
June 6	p. m.	[1] 2.15	e.	0.923	1.86	g.	0.711	0.800	0.868	0.922	0.957	0.971	0.979	0.980	0.984	0.978	2.02	1.086	0.850
7	a. m.	[2] 8.08	g.	.887	1.94	v. g.	.755	.814	.854	.905	.935	.958	.973	.980	.986	.995	2.02	1.041	.852
13	p. m.	[1] 6.04	v. g.	.877	2.02	v. g.	.734	.805	.843	.885	.914	.945	.961	.968	.975	.980	2.12	1.050	.835
14	a. m.	[1] 2.59	e.[2]	.908	1.89	e.	.765	.832	.875	.924	.953	.970	.978	.983	.987	.994	2.01	1.063	.854
17	a. m.	[2] 11.35	e.[2]	.893	1.92	e.	.736	.810	.862	.904	.935	.959	.975	.980	.980	.978	2.09	1.089	.820
20	p. m.	[1] 4.47	v. g.	.857	1.95	v. g.	.682	.756	.751	.869	.918	.942	.955	.963	.972	.981	2.12	1.082	.792
23	a. m.	[1] 4.86	e.[2]	.920	1.90	v. g.	.798	.845	.894	.942	.970	.985	.993	.995	.996	.996	2.00	1.053	.874
26	p. m.	[1] 6.57	g.	.897	1.90	v. g.	.727	.803	.853	.925	.970	.990	.995	.995	.995	.990	2.06	1.084	.827
28	a. m.	[1] 6.35	e.	.914	1.89	v. g.	.780	.843	.886	.932	.962	.974	.980	.982	.985	.986	2.01	1.063	.860
July 3	a. m.	....	e.	.922	1.84	v. g.	.773	.845	.885	.935	.960	.970	.973	.974	.975	.975	2.01	1.092	.844
6	p. m.	[1] 5.8	g.	.859	2.02	v. g.	.655	.766	.832	.890	.927	.946	.959	.970	.974	.981	2.10	1.040	.826
10	a. m.	....	e.	.877	1.87	e.	.711	.788	.834	.889	.923	.951	.964	.970	.975	.982	2.03	1.056	.830
11	p. m.	[1] 6.39	g.	.881	1.92	e.	.698	.792	.846	.902	.938	.961	.975	.977	.977	.974	2.03	1.057	.833
12	. m.	[2] 7.51	e.	.897	1.85	e.	.736	.803	.847	.903	.943	.957	.966	.975	.983	.985	2.03	1.097	.818
19	p. m.	[1] 3.02	g.	.881	1.93	v. g.	.735	.794	.837	.895	.921	.936	.950	.955	.962	.970	2.09	1.083	.813
21	p. m.	[1] 4.83	g.	(.881?)	1.89	e.	.730	.785	.832	.884	.928	.948	.957	.965	.969	.974	2.06	1.090	.808
22	a. m.	[2] 8.36	v. g.	.904	1.90	e.	.763	.812	.842	.910	.950	.968	.975	.980	.986	.989	2.05	1.079	.838
25	a. m.	[2] 8.58	e.	.875	1.86	e.	.710	.778	.822	.878	.910	.939	.950	.955	.962	.972	2.05	1.104	.793
25	p. m.	[1] 6.23	e.	.875	1.86	v. g.	.680	.775	.830	.891	.930	.946	.956	.963	.965	.970	2.05	1.104	.793
28	p. m.	[1] 6.79	e.	.893	1.88	g.	.725	.788	.839	.900	.926	.942	.950	.955	.960	.970	2.05	1.090	.820
31	p. m.	[1] 5.23	g.	.872	1.95	g.	.711	.775	.820	.885	.925	.945	.959	.965	.970	.978	2.08	1.067	.817
Aug. 3	p. m.	[1] 6.35	e.—	.898	1.91	e.	.696	.773	.829	.894	.931	.955	.966	.972	.980	.983	2.12	1.110	.809
9	p. m.	....	v. g.	.867	1.82	e.	.715	.780	.827	.882	.919	.940	.955	.964	.973	.985	1.98	1.088	.797
10	a. m.	....	e.	.908	1.91	v. g.	.745	.829	.872	.886	.945	.960	.969	.975	.980	.985	2.07	1.084	.838
11	a. m.	....	e.+	.900	1.88	v. g.	.735	.804	.850	.894	.940	.967	.977	.981	.985	.990	2.03	1.086	.830
11	p. m.	....	e.	......	......	e.	.711	.790	.831	.882	.925	.950	.963	.969	.970	.975	2.06	....	....
14	p. m.	[2] 11.18	e.[2]	.901	1.84	e.[2]	.726	.808	.856	.910	.940	.955	.965	.970	.974	.975	2.02	1.098	.820
17	a. m.	[2] 14.02	v. g.	.916	1.80	v. g.	.775	.840	.890	.906	.960	.970	.974	.977	.981	.983	1.98	1.103	.830
18	p. m.	[1] 8.47	g.	.856	1.92	e.	.710	.767	.817	.870	.922	.950	.955	.953	.956	.955	2.05	1.066	.803
21	p. m.	[1] 11.14	e.	.883	1.76	v. g.	.728	.794	.836	.902	.937	.952	.959	.965	.971	.976	2.00	1.133	.779
22	a. m.	[2] 15.60	e.	.910	1.80	p.	.776	.846	.884	.927	.950	.960	.968	.970	.976	.980	1.96	1.101	.826
24	p. m.	[1] 8.61	g.	.902	1.74	e.	.687	.779	.834	.899	.940	.959	.969	.975	.980	.986	2.01	1.156	.780
25	a. m.	[2] 11.83	e.	.890	1.83	e.	.795	.850	.874	.909	.931	.946	.952	.954	.954	.946	2.05	1.121	.794
25	p. m.	[1] 11.55	e.	.890	......	e.	.706	.785	.835	.885	.921	.946	.961	.970	.978	.991	2.08	1.137	.783
29	p. m.	[1] 7.48	e.	.906	1.73	g.	.765	.816	.860	.912	.946	.962	.970	.970	.979	.981	1.93	1.116	.812
30	a. m.	[2] 11.82	e.[2]	.895	1.75	g.	.730	.811	.868	.915	.943	.960	.972	.978	.984	.990	1.93	1.103	.811
30	p. m.	[1] 8.80	v. g.	.889	1.81	p.	.695	.780	.838	.897	.943	.969	.982	.986	.986	.985	1.96	1.083	.821
Sept. 5	p. m.	[1] 6.06	g.	.902	1.72	e.	.664	.771	.823	.878	.928	.951	.964	.971	.980	.986	2.01	1.169	.772
8	a. m.	[2] 9.17	e.	.877	1.84	v. g.	.705	.778	.827	.885	.925	.948	.962	.970	.972	.971	2.03	1.103	.795
8	p. m.	[1] 5.21	g.	.863	1.77	p.	.652	.723	.780	.846	.897	.934	.950	.955	.964	.965	2.00	1.131	.763
11	p. m.	[1] 6.83	p.	.912	1.76	e.	.700	.796	.841	.895	.942	.968	.978	.981	.983	.982	1.97	1.119	.815
13	p. m.	[1] 6.83	v. g.	.887	1.77	e.	.705	.793	.839	.888	.920	.945	.960	.966	.969	.975	1.95	1.102	.805
14	p. m.	[1] 6.47	e.	.904	1.82	e.	.761	.829	.867	.915	.938	.957	.965	.970	.975	.977	1.99	1.090	.830
15	p. m.	[1] 5.37	e.[2]	.897	1.88	e.	.758	.835	.869	.915	.945	.955	.963	.966	.969	.970	2.00	1.064	.843
16	a. m.	....	g.	......	......	g.	.762	.839	.880	.925	.951	.973	.985	.990	.993	.994	2.03	....	....
19	a. m.	[2] 10.87	e.	.885	1.88	g.	.722	.775	.829	.885	.921	.933	.940	.944	.950	.960	2.08	1.106	.800
21	a. m.	[2] 8.85	e.	.906	1.83	e.	.760	.825	.858	.904	.944	.968	.975	.979	.986	.993	1.98	1.082	.837
26	a. m.	[2] 8.54	v. g.	.896	1.81	p.	.750	.823	.865	.919	.943	.955	.965	.970	.975	.977	1.99	1.100	.815
27	a. m.	[2] 6.37	e.	.914	1.84	e.[2]	.774	.840	.879	.925	.949	.957	.964	.968	.970	.975	2.00	1.081	.845
Oct. 3	a. m.	[2] 10.12	e.	.908	1.82	e.	.751	.817	.853	.914	.950	.968	.974	.976	.983	.993	2.00	1.099	.826
4	a. m.	....	e.	.912	1.75	v. g.	.756	.826	.863	.904	.934	.950	.966	.974	.982	.989	1.98	1.131	.806
6	a. m.	....	e.	.911	1.86	e.	.764	.835	.867	.905	.939	.960	.970	.974	.977	.981	2.05	1.102	.827
10	a. m.	....	e.	.911	1.82	e.[2]	.769	.840	.880	.920	.954	.974	.982	.985	.987	.990	1.96	1.077	.846
12	p. m.	....	e.	.881	1.84	e.[2]	.698	.806	.855	.888	.930	.955	.969	.974	.979	.979	2.00	1.087	.810
18	a. m.	....	v. g.	.914	1.86	p.	.774	.847	.882	.927	.955	.966	.973	.975	.980	.986	2.01	1.081	.846
18	p. m.	....	v. g.	.915	1.76	p.	.705	.790	.848	.905	.955	.975	.984	.990	.993	.992	2.03	1.153	.794
20	a. m.	....	e.	.914	1.84	g.	.770	.828	.868	.920	.960	.972	.990	.993	.994	.992	1.98	1.076	.850
24	a. m.	[2] 6.42	e.	.906	1.85	v. g.	.764	.831	.874	.910	.939	.959	.970	.976	.981	.985	2.01	1.086	.834
26	p. m.	[1] 3.81	e.	.887	1.88	v. g.	.723	.811	.849	.895	.925	.950	.961	.966	.971	.982	2.07	1.101	.806
Mean.	......	....	......	.8948	......	......	......	......	......	......	......	......	......	......	......	......	2.024	1.093	.8191

[1] 6 p. m.   [2] 8 a. m.

TABLE 14.—*Results of "solar-constant" measurements, Mount Wilson observations*—Continued.

Date.	a. m. or p. m.	Pressure water vapor.[1]	Actinometry. Grade.	Actinometry. Apparent atmospheric transmission. a.	Actinometry. Apparent "solar constant." A_o.	Bolometry. Grade.	Atmospheric transmission for different wave-lengths. μ 0.40	μ 0.45	μ 0.50	μ 0.60	μ 0.70	μ 0.80	μ 0.90	μ 1.00	μ 1.20	μ 1.60	"Solar constant." E_o.	Ratio. $\frac{E_o}{A_o}$.	Atmospheric transmission. $\frac{A_o a}{E_o}$.
1906.		*mm.*																	
May 16	p. m.	......	v. g.	0.865	1.92	e.	0.701	0.759	0.790	0.849	0.887	0.911	0.925	0.930	0.934	0.935	2.069	1.078	0.802
17	a. m.	4.72	v. g.	.895	1.84	p.	.762	.837	.878	.920	.943	.955	.961	.964	.965	.970	1.972	1.072	.835
18[2]	p. m.	7.44	e.—	.873	1.92	p.	.750	.829	.865	.904	.921	.934	.942	.945	.949	.950	2.031	1.058	.825
19	a. m.	5.46	v. g.	.887	1.90	e.	.762	.823	.857	.890	.909	.920	.925	.929	.932	.935	2.089	1.099	.807
29	a. m.	4.22	v.g.+	.908	1.90	e.	.793	.858	.894	.920	.941	.953	.959	.961	.964	.965	2.008	1.057	.859
30	a. m.	5.03	g.	.908	1.85	g.	.744	.798	.840	.904	.960	.972	.978	.980	.985	.987	2.013	1.082	.839
June 6	a. m.	5.28	e.	.902	1.83	e.	.749	.813	.846	.893	.933	.950	.964	.970	.974	.979	2.031	1.110	.813
7	a. m.	4.65	e.	.910	1.86	v. g.	.776	.850	.886	.919	.944	.955	.964	.966	.968	.969	2.009	1.080	.843
9	a. m.	6.50	v.g.+	.900	1.82	e.	.753	.815	.857	.910	.945	.961	.970	.974	.976	.980	1.974	1.085	.830
12	p. m.	11.30	e.	.879	1.76	v. g.	.721	.798	.841	.895	.929	.944	.951	.956	.961	.965	2.036	1.157	.760
15	a. m.	8.41	e.—	.902	1.87	e.	.758	.822	.860	.915	.949	.965	.973	.978	.984	.990	2.019	1.080	.835
16	a. m.	7.21	v. g.	.897	1.79	g.	.763	.833	.870	.915	.940	.954	.964	.970	.975	.980	2.002	1.118	.802
19	a. m.	6.40	e.	.904	1.82	e.	.755	.824	.865	.914	.940	.957	.969	.972	.977	.983	1.987	1.092	.828
20	a. m.	6.53	e.—	.900	1.90	e.	.760	.819	.855	.902	.935	.956	.967	.970	.975	.975	2.050	1.079	.834
22	a. m.	6.55	e.	.900	1.90	g.	.772	.829	.862	.908	.935	.946	.955	.960	.965	.972	2.047	1.077	.836
23	a. m.	6.53	e.	.893	1.85	e.—	.754	.834	.867	.914	.939	.951	.960	.967	.974	.980	2.004	1.083	.824
29	a. m.	4.85	v. g.	.895	1.88	e.	.760	.815	.848	.890	.925	.950	.967	.972	.976	.984	2.026	1.078	.830
30	a. m.	6.45	e.	.881	1.88	e.	.744	.809	.850	.894	.925	.945	.955	.961	.968	.973	2.022	1.074	.820
July 3	a. m.	8.41	e.	.867	1.87	e.	.725	.786	.831	.877	.912	.931	.944	.951	.960	.975	2.036	1.089	.796
6	a. m.	9.80	e.	.869	1.81	e.	.711	.790	.835	.895	.934	.947	.954	.956	.959	.961	1.988	1.098	.791
10	a. m.	9.58	v. g.	.871	1.77	e.	.700	.775	.822	.879	.914	.935	.945	.952	.960	.970	1.988	1.123	.776
11	a. m.	8.69	e.	.851	1.83	e.	.673	.755	.808	.868	.905	.925	.939	.948	.956	.961	2.018	1.103	.771
17	a. m.	7.52	e.	.889	1.83	e.	.726	.796	.835	.886	.939	.956	.964	.969	.974	.981	2.023	1.105	.805
18	a. m.	8.10	e.	.889	1.83	e.	.727	.801	.846	.900	.945	.958	.966	.971	.977	.981	2.015	1.101	.807
21	a. m.	9.63	v. g.	.857	1.82	e.	.695	.765	.810	.865	.895	.920	.934	.943	.955	.971	2.079	1.142	.750
24	a. m.	11.30	e.	.887	1.64	v.g.—	.700	.790	.850	.900	.926	.940	.950	.958	.963	.970	2.046	1.247	.711
27	a. m.	8.86	e.	.893	1.79	e.	.765	.823	.859	.905	.935	.955	.964	.966	.971	.975	1.998	1.116	.800
28	a. m.	7.98	e.	.879	1.86	e.	.726	.805	.845	.895	.920	.938	.950	.954	.960	.966	2.047	1.101	.798
31	a m.	7.80	e.	.891	1.94	e.	.751	.817	.857	.902	.932	.946	.955	.964	.970	.978	2.072	1.068	.834
Aug. 1	a. m.	5.89	e.	.900	1.92	e.	.765	.827	.865	.916	.941	.955	.961	.965	.969	.972	2.048	1.067	.843
3	a. m.	5.16	e.	.906	1.85	e.	.760	.825	.865	.915	.940	.955	.965	.972	.976	.983	2.023	1.094	.828
4	a. m.	7.04	g.	.891	1.88	e.[2]	.750	.818	.860	.907	.935	.950	.960	.965	.969	.979	2.031	1.080	.825
7	a. m.	5.83	e.	.900	1.89	e.	.756	.828	.865	.915	.953	.965	.972	.974	.975	.977	2.033	1.076	.836
8	a. m.	5.05	e.	.908	1.88	e.	.764	.827	.865	.910	.940	.955	.964	.970	.979	.990	2.029	1.079	.841
14	a. m.	9.59	v.g.+	.867	1.84	v.g.—	.720	.786	.826	.878	.926	.955	.969	.975	.983	.985	2.020	1.098	.790
15	a. m.	7.80	e.	.875	1.73	e.	.702	.774	.820	.877	.921	.945	.957	.962	.969	.976	1.966	1.136	.770
17	a. m.	10.71	e.	.879	1.77	e.—	.736	.795	.834	.889	.925	.949	.961	.967	.970	.970	1.964	1.110	.792
21	a. m.	4.88	e.—	.889	1.99	e.	.754	.815	.861	.915	.938	.950	.959	.964	.969	.971	2.075	1.043	.852
23	a. m.	4.29	e.	.908	1.93	e.	.766	.833	.878	.924	.950	.965	.975	.979	.982	.986	2.040	1.057	.859
25	h. m.	4.89	e.	.897	1.87	e.	.742	.806	.845	.904	.940	.956	.966	.975	.987	.995	2.029	1.085	.827
29	a. m.	6.80	e.	.845	1.77	v.g.—	.655	.733	.777	.850	.898	.928	.944	.952	.962	.975	1.980	1.119	.755
31	a. m.	7.45	e.	.877	1.79	e.	.715	.780	.825	.883	.914	.934	.949	.956	.968	.978	2.017	1.127	.750
Sept. 1	a. m.	5.84	e.	.873	1.96	e.	.715	.786	.830	.875	.912	.932	.945	.951	.956	.960	2.111	1.077	.810
4	a. m.	5.10	p.	.914	1.75	p.	.735	.814	.865	.917	.943	.955	.961	.965	.969	.972	2.028	1.159	.789
5	a. m.	5.66	e.	.897	1.84	e.	.755	.815	.857	.910	.945	.965	.974	.975	.977	.975	2.009	1.092	.821
8	a. m.	10.27	e. ?	.910	1.75	g.	.769	.835	.879	.937	.965	.976	.980	.984	.986	.990	1.955	1.114	.817
9	a. m.	9.37	e.	.895	1.90	e.	.753	.818	.860	.908	.936	.955	.964	.970	.976	.985	2.041	1.074	.833
11	a. m.	5.28	e.	.902	1.94	e.—	.767	.830	.868	.915	.944	.961	.972	.980	.985	.991	2.026	1.044	.864
18	a. m.	3.87	e.	.914	1.87	e.[2]	.765	.832	.875	.925	.952	.965	.971	.979	.985	.987	2.035	1.088	.840
20	a. m.	5.31	v.g.—	.893	1.82	e.	.740	.805	.849	.902	.936	.950	.960	.966	.971	.982	2.009	1.104	.809
25	a. m.	5.32	v. g.	.897	1.84	v.g.+	.768	.830	.865	.915	.945	.959	.965	.969	.974	.980	2.006	1.090	.823
28	a. m.	5.79	v. g.	.887	1.88	v.g.+	.745	.814	.854	.912	.943	.955	.962	.966	.972	.975	2.058	1.095	.810
Oct. 2	a. m.	6.55	v. g.	.885	1.86	g.	.758	.803	.847	.900	.936	.952	.960	.965	.969	.971	2.022	1.087	.814
4	a. m.	2.79	v. g.	.897	1.86	e.	.750	.810	.855	.910	.944	.961	.969	.971	.975	.977	1.992	1.071	.837
6	a. m.	2.75	v. g.	.914	1.84	e.	.770	.832	.870	.918	.950	.970	.980	.985	.989	.994	2.003	1.089	.839
9	a. m.	2.90	e.	.907	1.87	e.	.755	.833	.872	.912	.950	.968	.975	.980	.986	.990	2.003	1.071	.847
11	a. m.	3.35	e.	.902	1.82	e.	.736	.799	.840	.886	.925	.942	.950	.954	.960	.964	2.046	1.124	.802
13	a. m.	2.46	g.	.906	1.82	e.	.755	.828	.869	.915	.946	.960	.970	.974	.977	.980	1.984	1.090	.831
16	a. m.	3.28	v. g.	.918	1.88	g.	.767	.830	.868	.917	.948	.964	.972	.977	.980	.984	2.043	1.087	.845
18	a. m.	4.24	v. g.	.910	1.81	g.	.770	.850	.889	.938	.968	.984	.992	.995	.998	.999	1.930	1.066	.854
20	a. m.	1.79	v. g.	.925	1.83	e.	.765	.834	.875	.920	.950	.968	.979	.983	.986	.990	1.980	1.082	.855
23	a. m.	2.17	v. g.	.912	1.85	e.	.746	.827	.871	.922	.954	.969	.978	.984	.989	.992	2.007	1.085	.841
Mean.	......	......	......	.8926	......	......	......	......	......	......	......	......	......	......	......	......	2.020	1.094	.8163

[1] Taken during midst of observations.

TABLE 14.—*Results of "solar-constant" measurements, Washington observations*—Continued.

Date. p. m.	Pressure water vapor, 2 p. m.	Actinometry.			Bolometry.											"Solar constant." E_o.[3]	Ratio. $\frac{E_o}{A_o}$	Atmospheric transmission $\frac{A_o a}{E_o}$.
		Grade.[1]	Apparent atmospheric transmission. a.	Apparent "solar constant." A_o.	Grade.[2]	Atmospheric transmission for different wave-lengths.												
						μ 0.40	μ 0.45	μ 0.50	μ 0.60	μ 0.70	μ 0.80	μ 0.90	μ 1.00	μ 1.20	μ 1.60			
1902.	*mm.*																	
Oct. 9	......	g.	0.800	1.886	g.	......	......	0.70	0.78	0.84	0.87	0.89	0.90	0.91	0.93	2.15	1.140	0.702
15	......	g.	.787	2.009	g.	......	......	.73	.78	.86	.89	.90	.91	.93	.96	2.15	1.070	.735
22	......	p.	......	......	g.	......	......	.84	.82	.88	.91	.93	.94	.94	.95	2.12	......	......
1903.																		
Feb. 19	0.71	v. g.	.748	1.880	v. g.	0.53	0.62	.62	.67	.75	.80	.82	.85	.86	.95	2.226	1.202	.622
Mar. 25	4.57	p.	.655	2.058	e.	.47	.50	.57	.66	.72	.76	.79	.81	.84	.88	2.146	1.043	.628
26	5.36	g.	.701	1.755	e.	.52	.58	.62	.68	.77	.80	.81	.83	.85	.89	2.069	1.179	.595
Apr. 29	8.31	p.	......	......	e.	.46	.49	.56	.66	.72	.76	.77	.80	.83	.88	1.877	......	......
July 7	13.74	p.	.692	1.897	p.	.42	.60	.66	.69	.77	.82	.85	.86	.88	.89	2.050	1.081	.640
Aug. 24	14.66	p.	......	......	g.	.39	.52	.60	.59	.78	.84	.86	.87	.89	.90	1.863	......	......
Oct. 14	8.74	g.	.791	1.764	v. g.	.64	.70	.76	.80	.85	.88	.89	.91	.91	.92	1.884	1.068	.740
29	5.56	p.	.738	1.826	v. g.	.52	.59	.65	.75	.80	.82	.84	.85	.88	.91	1.890	1.035	.713
Dec. 7	3.33	v. g.	.794	1.672	v. g.	.58	.67	.76	.81	.84	.87	.89	.92	.93	.95	1.900	1.136	.699
23	3.30	p.	.838	1.677	v. g.	.67	.71	.75	.80	.86	.89	.90	.91	.92	.94	1.906	1.143	.733
1904.																		
Jan. 27	1.45	p.	.826	1.619	g.	.60	.67	.73	.73	.79	.84	.89	.91	.91	.91	1.935	1.195	.691
Feb. 11	0.81	p.	.759	1.803	v. g.	.42	.55	.58	.59	.70	.78	.84	.89	.92	.95	2.175	1.206	.629
Mar. 4	1.45	g.	.776	1.794	g.	......	.54	.68	.73	.74	.83	.88	.88	.89	.94	2.078	1.158	.670
Apr. 4	......	p.	.782	1.847	p.	.42	.63	.67	.72	.79	.85	.88	.89	.91	.94	2.031	1.100	711
May 12	6.02	v. g.	.781	1.705	p.	.35	.55	.71	.79	.83	.86	.89	.90	.92	.95	2.080	1.220	.640
25	......	p.	.703	1.837	g.	.52	.56	.58	.67	.74	.79	......	......	.80	......	2.165	1.156	.608
28	6.50	g.	.752	1.896	v. g.	.40	.57	.63	.77	.83	.87	.90	.90	.90	.91	2.011	1.061	.709
Sept. 22	......	p.	.805	1.857	g.	.55	.65	.72	.81	.86	.88	.89	.90	.90	.90	2.095	1.128	.714
Oct. 5	9.83	v. g.	.740	1.876	v. g.	.48	.58	.65	.74	.80	.84	.86	.87	.89	.90	2.232	1.190	.622
21	7.29	g.	.845	1.850	e.	.60	.72	.78	.86	.90	.93	.94	.95	.97	.98	2.005	1.084	.779
Nov. 16	4.14	v. g.	.789	1.774	p.	.54	.62	.65	.74	.85	.88	.90	.90	.91	.91	1.870	1.054	.749
1905.																		
Jan. 26	0.81	e.	.861	1.764	v. g.	.59	.72	.77	.78	.85	.90	.90	.90	.90	.92	2.090	1.185	.726
Feb. 7	1.78	e.	.799	1.820	v. g.	......	.66	.69	.76	.83	.85	.87	.88	.91	.93	2.017	1.108	.721
14	0.48	g.	.819	2.081	g.	.53	.70	.72	.77	.84	.87	.89	.91	.95	.91	2.379	1.143	.717
May 20	3.76	g.	.783	1.897	g.	.53	.71	.68	.76	.82	.88	.92	.92	.90	.84	2.089	1.101	.711
June 3	......	g.	.760	1.901	g.	.45	.56	.62	.74	.78	.85	.90	.92	.93	.91	2.151	1.132	.671
Sept. 19	17.37	g.	.828	1.663	p.	.55	.70	.79	.81	.93	.93	.95	.95	.93	.93	1.814	1.089	.760
26	4.57	v. g.	.823	1.843	e.	.60	.70	.76	.80	.87	.90	.89	.89	.89	.89	2.106	1.143	.720
Oct. 4	7.29	e.	.799	1.692	e.	.64	.66	.74	.77	.82	.83	.85	.87	.88	.90	1.982	1.171	.682
Nov. 1	3.99	p.	.836	1.675	g.	.54	.66	.72	.78	.87	.91	.93	.95	.97	.97	1.912	1.141	.733
Dec. 4	2.13	g.	.806	1.766	v. g.	.59	.64	.71	.73	.80	.84	.88	.90	.92	.96	2.036	1.153	.699
1906.																		
Jan. 9	1.96	v. g.	.832	2.070	p.	......	.70	.75	.79	.82	.89	.91	.94	.95	.97	2.252	1.088	.764
Feb. 15	2.16	g.	.794	2.074	v. g.	.50	.63	.71	.79	.85	.89	.91	.92	.91	.93	2.215	1.068	.743
May 24	10.06	p.	.673	1.971	p.	......	.53	.61	.70	.76	.82	.84	.85	.86	.85	2.157	1.094	.615
29	9.83	v. g.	.811	1.926	e.	.45	.61	.74	.80	.89	.89	.90	.91	.95	.93	2.154	1.118	.725
Nov. 6	3.68	v. g.	.817	1.987	g.	.59	.70	.69	.82	.90	.93	.94	.93	.93	.92	2.093	1.053	.776
22	4.83	v. g.	.886	1.737	v. g.	.58	.76	.82	.87	.94	.94	.95	.96	.97	.95	2.046	1.178	.752
Dec. 26	1.90	v. g.	.830	1.934	g.	......	.66	.74	.80	.88	.89	.91	.92	.92	......	2.125	1.098	.756
1907.																		
Feb. 15	1.45	e.	.881	1.784	e.	.71	.77	.84	.87	.90	.93	.94	.96	.96	.96	1.972	1.105	.797
May 13	[4]9.14	v. g.	.766	1.878	e.	.55	.59	.67	.70	.82	.85	.90	.93	.94	.89	2.119	1.128	.679
14	14.60	e.	.745	1.838	e.	.46	.54	.63	.71	.78	.82	.85	.87	.90	.98	2.074	1.128	.660
Mean.	......	......	.7866	......	......	......	......	......	......	......	......	......	......	......	......	2.061	1.1237	.7009

[1] From March 25, 1903, to February 11, 1904, the pyrheliometer was read only a few times on each day of observation, as the need was not then recognized of employing pyrheliometer readings to correct the bolometric observations to constant sensitiveness of apparatus.

[2] Prior to those of January 26, 1905, only the observations of February 19, 1903, and March 4, 1904, have been reduced with special attention to the correction for change of sensitiveness of the apparatus. All later observations have this correction, excepting February 7 and June 3, 1905. The correction is usually small. In the older reductions, when it was not applied according to our modern practice, there is still some approximation toward it, because two reductions were made for each day of observation, and these were based on different pyrheliometer readings taken one or two hours apart. The values given above in such instances are mean values from the two reductions.

[3] Results of some of the days here given have been published elsewhere with slightly higher values. The changes have been made to reconcile them all to a consistent scale of pyrheliometry in accordance with Table 2A of Chapter II.

[4] 8 p. m.

Chapter VI.

APPLICATIONS OF SOLAR RADIATION MEASUREMENTS.

1. THE MEAN VALUE OF THE "SOLAR CONSTANT" OF RADIATION.

There have been presented in the preceding chapter the results of 165 different determinations of the value of the "solar constant" of radiation. Forty-four of these have been computed from Washington observations scattered over the interval from October, 1902, to May, 1907. Their mean is 2.061 calories per square centimeter per minute.[1] Fifty-nine are from Mount Wilson observations of 1905, and their mean is 2.024. The remainder are from Mount Wilson observations of 1906, and their mean is 2.020.

As will be shown in the next section, there is strong evidence that the intensity of solar radiation fluctuates considerably, so that the values determined in this research, being all representative of the conditions of great sun-spot frequency, may not give a fair mean value for the "solar constant." The well established sun-spot period of eleven years in terrestrial temperatures indicates that the solar radiation is of greater average intensity during the period of minimum sun spots. Hence we incline toward the belief that the mean value of the "solar constant" will be found slightly greater than our results would indicate, and we will assign, in round numbers, 2.1 calories per square centimeter per minute to be the probable mean value of the "solar constant" of radiation.

2. THE VARIABILITY OF THE SUN'S RADIATION.

Among the 165 determinations of the "solar constant" which have been given there are to be found, as the results of excellent determinations, values as low as 1.9 calories and as high as 2.2 calories. Even if we confine ourselves to Mount Wilson determinations alone, the range is from 1.93 to 2.14. The question arises whether these variations are due to real changes in the intensity of the sun's radiation, to errors in estimating the transmission of the rays in the atmosphere, or to accidental errors of the measurements by the pyrheliometer of the intensity at the earth's surface.

Taking the last proposed explanation first, the answer is plain that it is not possible that changes of the magnitude in question are due to errors of the pyrhe-

[1] Attention is again drawn to the fact that the scale of values here used may differ slightly from the true calorie, and, according to the evidence of the continuously recording water pyrheliometer, is about 1.4 per cent too high.

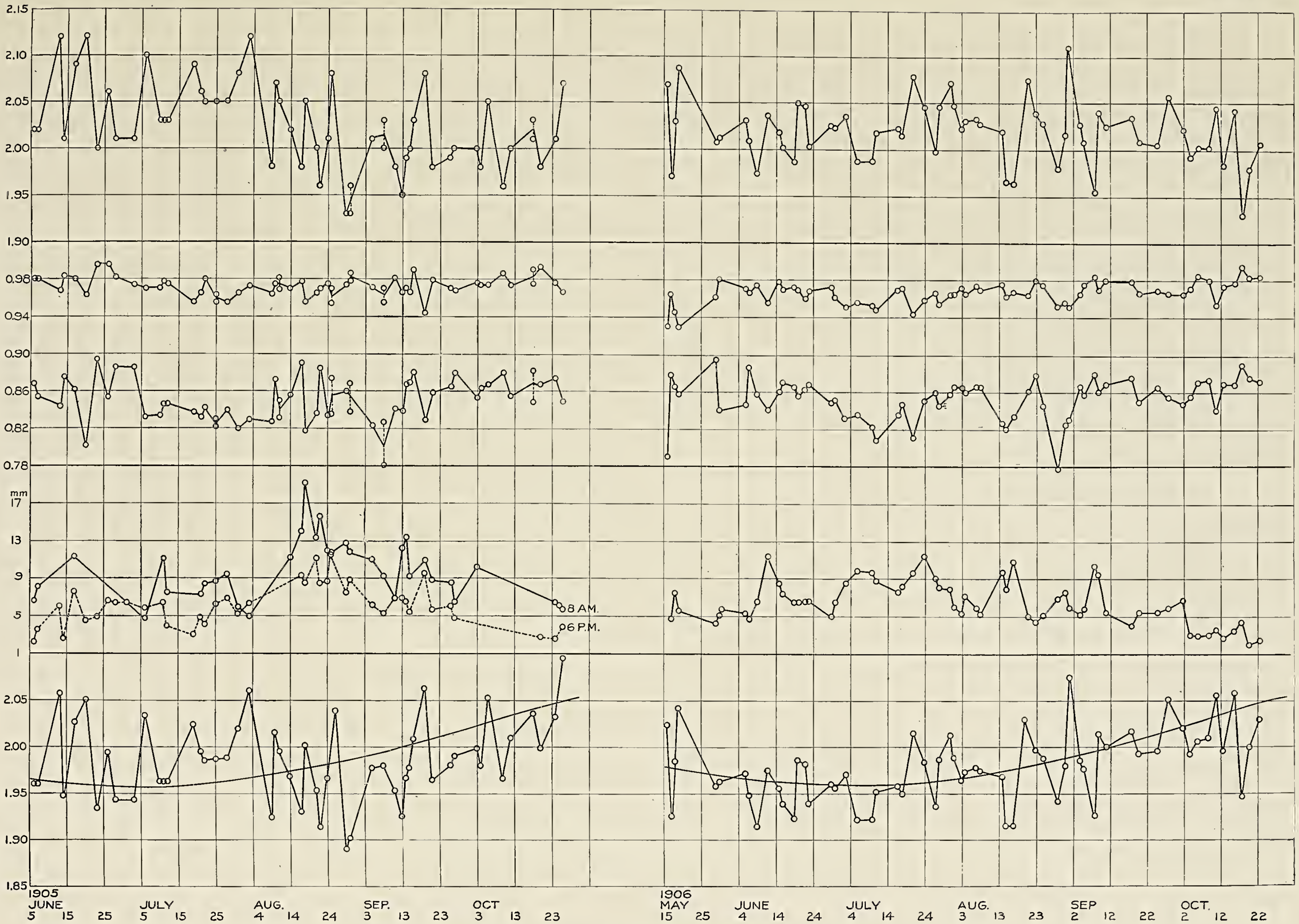
liometer measurements. In this connection the reader may consult Chapters II and IV, and especially in Table 2A the comparisons of pyrheliometers II, III, IV, and VI, which were employed on Mount Wilson. From these comparisons it appears that single readings of these pyrheliometers are seldom in error, relatively to other readings, by as much as 1.5 per cent. It should be remembered that the results of a day depend not on a single measurement, but on a group of from ten to twenty of them distributed over several hours.

As we can never conduct our measurements beyond the limit of the atmosphere, we can never have positive proof that our values of the "solar-constant" are correct, and it is possible that the fluctuation of the results may be due to errors of estimation of the transmission of the atmosphere. Referring, however, to Chapters IV and V, the magnitude of the fluctuation of the "solar-constant" determinations resulting from excellent observations appears to be far beyond the limit which probability assigns to all causes combined, including errors of estimation of atmospheric transmission.

But if some important error of procedure or of observation has been overlooked and the fluctuations in the results are to be attributed to errors in estimating the transparency of the atmosphere, then it would seem likely that there would be found some connection between the fluctuations of the "solar-constant" results and the fluctuations of humidity and transparency of the atmosphere; or, in other words, it would seem probable that the known variations in the quality of the atmosphere from day to day would produce some evident influences on the results.

In order to see if this is so, the reader is invited to inspect Plate XV. The first line gives all the results of "solar-constant" measurements obtained on Mount Wilson in 1905 and 1906 reduced to mean solar distance; the second and third lines give the transmission coefficients of the atmosphere determined by bolometric methods for wave-lengths 1.0μ and 0.5μ; the fourth line gives the pressure of aqueous vapor (in millimeters of mercury) which prevailed on the days of observation. There can not be found any relation, either direct or inverse, which holds consistently to connect the fluctuations of line 1 with those of lines 2, 3, or 4, and hence we may feel added confidence that the fluctuations of the determinations of the "solar constant" are not attributable to errors of the estimation of the transparency of the atmosphere.

If it be admitted that a change of 2 per cent in the solar radiation would probably be recognized in the Mount Wilson experiments, then the change of intensity which accompanies the variation in the distance between the earth and the sun should be apparent, unless obscured by irregular changes in the sun's emission. In line 5 of Plate XV are given all the results included in line 1, but in line 5 no correction has been applied to reduce them to mean solar distance, so that they stand exactly as determined at the limit of the atmosphere. The smooth curve is drawn



Results of "Solar-constant" Measurements on Mount Wilson.

to represent that known variation of the intensity of solar radiation which depends on the change of solar distance. It will be seen that the observations of 1906 are in the mean in excellent accord with this line throughout nearly the whole period of observation. Those of 1905 run nearly parallel to it in June and July, and again in September and October, but indicate a change of solar radiation during August.

This comparison shows that there is little doubt of the adequacy of the measurements to recognize a slow change of solar radiation of 3 per cent, or even much less, and it seems almost impossible to avoid admitting, in view of all that has been said, that the gradual change which appeared in August, 1905, was a real change in the intensity of solar radiation.

But there are also shown numerous changes of short period in the results of both Mount Wilson seasons, and we next inquire if these, too, are attributable to the sun, or if, on the other hand, they are merely the accidental errors of isolated observations. The magnitudes of many of them exceed 4 per cent, and the accuracy of the observations seems to be so great that errors of this magnitude would be very rare.

It is shown in works on least squares that the probable number of occurrences of accidental errors of different magnitudes is a certain function of the average deviation of the measurements from their mean. In the following table is shown the number of observations made on Mount Wilson in 1905 and 1906 whose departure from the means lay between 1, 2, 3, 4, and 5 halves of the value of the average deviation, and also the numbers which would be expected between these magnitudes on the assumption that the departures were of a merely accidental nature. In order to avoid the influence of the marked change which took place in August, the observations of 1905 have been divided in two lots in taking the mean values and departures, the first lot being prior to and including August 11, the second lot after that date. The first mean is 2.052, the second 2.002, and the average deviation for the whole season is 0.031. The departures for the year 1906 have been taken about the mean value 2.020, and the average deviation is 0.023.

	Between—					
	0 and $\frac{1}{2}$ average deviation.	$\frac{1}{2}$ and 1 average deviation.	1 and $\frac{3}{2}$ average deviation.	$\frac{3}{2}$ and 2 average deviation.	2 and $\frac{5}{2}$ average deviation.	$\frac{5}{2}$ average deviation and ∞.
Observed number of departures........	38	36	20	8	16	3
Computed number of departures.......	38	31	23	16	8	5

The result of the above comparison, while it indicates a decided departure of the distribution of the deviations of magnitude between 3/2 and 5/2 the average deviation from that which the theory of accidental errors would predict, can not

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of itself be considered decisive evidence that the small departures we are considering are not of an accidental character.

But referring to Plate XV the reader may observe that the changes from a high value to a low one are often of a progressive character, not apt to be the result of accident. Often there are two, and sometimes three or four intermediate values which lead the curve smoothly from a crest to a trough; and where this is the case one is disinclined to attribute the change to mere accidental error. If there was corresponding to these progressive changes of short period a consistent connection, either direct or inverse, between line 1 and either of lines 2, 3, or 4 of Plate XV, it would be natural to attribute the changes to atmospheric causes. This resource fails signally, and we therefore incline to believe that the existence of real fluctuations of short period in the intensity of the sun's radiation is the most probable explanation of the results obtained on Mount Wilson.

Of the reality of the apparent considerable decrease of radiation which occurred in August, 1905, there is, as has been said, little doubt.

The variations of solar radiation which have apparently been observed in Washington extend over a considerably greater range than those which are indicated by the Mount Wilson observations. Unfortunately the accuracy of the Washington work is of a lower order than that on Mount Wilson, because of the greater opaqueness and more variable character of the atmosphere above the lower altitude station. Furthermore, the days apparently suitable for good observing have been so widely scattered as to prevent the making of numerous observations to remove the uncertainty of the separate results; but, with due allowance for these unfortunate conditions, there seems still to be ground for belief in the reality of many of the changes apparently observed.

Some idea of the degree of accuracy of Washington observations may be obtained by a comparison of the results obtained at Washington and Mount Wilson nearly simultaneously. As shown by the tables given in the preceding chapter, there were several days during 1905 and 1906 when observations were made almost simultaneously at Washington and Mount Wilson. A comparison of the results obtained is given in the following table. When no estimates were made on Mount Wilson on the same day as those in Washington the most probable value was indimated from the nearest days of observation. Such estimates are given in brackets.

TABLE 15.—*Comparison of Washington and Mount Wilson "solar-constant" determinations.*

	1905.					1906.		
	June 3.	Sept. 19.	Sept. 26.	Oct. 4.	Nov. 6.	May 24.	May 29.	Nov. 6.
Washington result	2.132	1.814	2.106	1.982	2.093	2.157	2.154	2.093
Grade	g	p	e	e–	g	p	e	g
Mount Wilson result	[2.06]	2.08	1.99	1.98	[2.05]	[2.08]	2.008	[2.02]
Grade	....	e–	v g	e	....	....	e	....
Percentage deviation	+3.5	–13.0	+5.3	+0.1	+2.1	+3.7	+7.3	+3.6

With the exception of September 19, when the Washington observations are rated as "poor," and may therefore be omitted from this comparison, all the Washington results are greater than those given for Mount Wilson, and the average departure is 3.6 per cent. The average deviation from this mean departure is 1.5 per cent. If we admit a real tendency to higher results at Washington, which might be in part attributable to a possible error of the comparison of pyrheliometers, or more probably to some regular change in the transparency of the atmosphere apt to occur during observing hours at one station or the other, or both, of such a nature as to cause an overestimate of the atmospheric transmission at Mount Wilson [1] or an underestimate at Washington, then we might regard 1.5 per cent as the average deviation of good Washington results attributable to accidental error. If this be admitted, the large change of the order of 15 per cent which occurred apparently in 1903 would certainly not be attributable to accidental error. The reader may find other changes of from 7 to 10 per cent in magnitude indicated in subsequent years by the Washington observations. The question as to the genuineness of each can not be absolutely decided, but admitting the strong evidence furnished by observations at Washington and Mount Wilson of 1903 and 1905, respectively, that changes in solar radiation of considerable magnitude do occur, we incline to credit the reality of some of the changes indicated.

It will be recalled that a variation of solar radiation was thought by Langley to be a possible explanation of the change noted in 1903, and the case was greatly strengthened in his paper on the subject by a comparison of solar radiation with the temperature departures for that year.[2]

A determination of the magnitude of the temperature departures on the earth's surface, which ought to follow changes of from 5 to 15 per cent in solar radiation, and a discussion of the temperature of large land areas of the globe for the last quarter century, will be given in Chapter V of Part II of this volume. The results of the temperature discussion are by no means contrary to the view that temporary changes of from 5 to 15 per cent in solar radiation may occur. We may then conclude that we have obtained positive evidence which strongly indicates a substantial variability of the sun and that there is nothing contrary to this conclusion arising from a study of the earth's temperature.

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[1] Attention was drawn in Chapter IV to the increase of water-vapor pressure which occurred toward noon daily on Mount Wilson as a possible small source of error tending to diminish the results obtained there. An increase of haziness toward evening often occurs at Washington and might produce too high results there.

[2] See Astrophysical Journal, June, 1904.

3. THE NORMAL ENERGY CURVE OF THE SOLAR SPECTRUM OUTSIDE THE ATMOSPHERE.

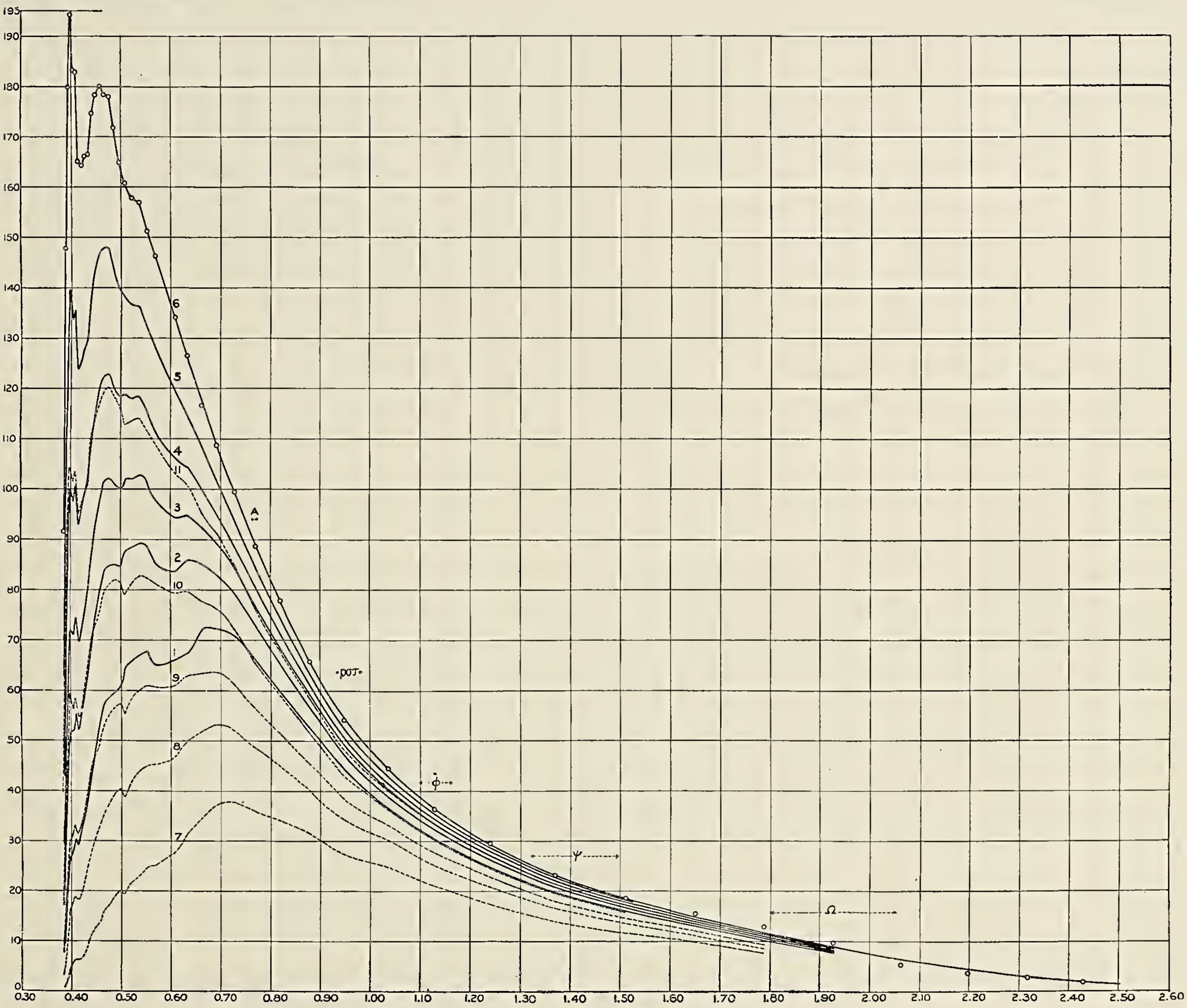
It is well known that in the solar spectrum as observed at the earth's surface the rays of shorter wave-length, such as violet and blue, are much enfeebled by the effect of the atmosphere, so that the color of the sun, and indeed of all the heavenly bodies, is more yellowish than would be the case if they could be seen by an observer in free space. The distribution of the intensities in the solar spectrum outside the atmosphere has been approximately determined here as a part of the procedure for fixing the value of the "solar constant," and the results of about a dozen of the best determinations will now be presented.

The procedure employed in the determination is as follows: Bolographs of the solar spectrum are obtained frequently upon a good day during the hours when the path of the sun rays in the atmosphere is rapidly changing, and from these are computed the coefficients of transmission of the atmosphere for rays of different wave-lengths. Near noon measurements are made of the reflecting power of the cœlostat mirrors, and of the relative transmission of the spectroscope for rays of different wave-lengths, as explained in Chapter III. By the aid of the coefficients of atmospheric and instrumental transmission thus determined, the distribution of energy in the prismatic spectrum as it would be outside the atmosphere can be inferred. A carefully drawn curve is made having the prismatic deviations, θ, as ordinates, and wave-lengths, λ, as abscissæ, and from this curve the values of the tangents, corresponding to $\frac{d\theta}{d\lambda}$, are obtained for numerous values of the wave-lengths. These numbers are used as multipliers to transform the prismatic energy spectrum to a form in which the scale of abscissæ is that of wave-lengths.

In the latter form the energy curve of the sun outside the atmosphere has a very strong maximum between wave-lengths 0.4μ and 0.5μ, and falls off with extreme rapidity toward the shorter wave-lengths. For convenience the separate determinations are given on the prismatic scale in Table 16. Figure 6, Plate XVI, shows the mean result obtained at Mount Wilson transferred to the normal or wave-length scale.[1]

The separate determinations given in Table 16 are reduced to agree in scale as nearly as possible in the infra-red region of the spectrum, in order that the divergencies may appear chiefly in the region of the shorter wave-lengths where the absorption of the solar envelope of the earth's atmosphere and of the optical apparatus unite to produce most effect; for this is certainly the region where the divergencies would most naturally be expected. No attempt has been made to show the Fraunhofer lines in the curves; and atmospheric lines are of course absent.

[1] This may be compared with the Washington work included in the publication of Abbot, 1903. See Smithsonian Miscellaneous Collections, vol. 45, p. 74. Undoubtedly the present determination is far more accurate than that published by Abbot, but the agreement of the two is generally good, excepting as to the exact form of the curve between 0.4μ and 0.5μ.



Normal Spectrum Energy Curves.

Table 16.—*Intensity of solar spectrum outside the atmosphere from Mount Wilson determinations.*

Prismatic deviation from F line.	Mean intensity, prismatic scale.	Percentage deviations from mean intensity prismatic scale.									$\frac{d\theta}{d\lambda}$	Mean intensity, normal scale.	Wave-length.
		1905.							1906.				
		June 17.	July 10.	July 11.	July 12.	Aug. 3.	Aug. 10.	Oct. 6.	Aug. 7.	Aug. 8.			μ
+150′	115	+25	−16	+29	....	+24	....	−22	−18	−25	7.990	918	0.387
140	201	+10	−20	+20	+11	− 4	+35	−35	− 6	−13	7.360	1,479	.390
130	266	+ 9	+ 3	+14	....	− 6	....	−16	+ 2	− 6	6.770	1,800	.3942
120	312	+11	− 2	+13	+ 5	+ 7	+20	−31	− 7	0	6.230	1,944	.3987
110	316	+23	+ 7	+23	....	−10	....	−30	− 4	− 9	5.800	1,833	.4037
100	337	+18	− 6	+21	+13	− 8	+12	−26	− 6	−15	5.430	1,830	.4091
90	324	+21	− 1	+17	....	− 9	....	−19	− 1	− 8	5.100	1,652	.4147
80	343	+11	− 1	+16	0	− 7	+ 9	−19	+ 1	−12	4.795	1,644	.4210
70	368	+11	− 8	+21	....	− 3	....	− 9	− 3	− 9	4.515	1,662	.4275
60	392	+ 9	−14	+22	− 6	+ 1	+ 6	− 7	− 6	−10	4.250	1,666	.4343
50	438	+16	− 8	+16	....	− 2	....	− 5	− 6	−12	3.990	1,748	.4417
40	477	+11	+ 1	+15	− 1	− 6	− 3	+ 2	− 5	−14	3.743	1,785	.4494
30	515	+14	+ 1	+ 6	....	− 3	....	− 3	− 5	−10	3.500	1,802	.4578
20	547	+14	− 2	+ 6	+ 1	+ 4	+ 3	− 6	−10	−11	3.266	1,786	.4666
+ 10	586	+10	− 5	+ 6	....	+ 7	....	− 2	− 8	− 9	3.039	1,781	.4762
0	610	+11	− 3	+ 3	− 2	+ 9	+ 5	− 9	− 5	− 9	2.818	1,719	.4861
− 10	634	+ 9	− 5	+ 6	....	+ 6	....	− 2	− 4	− 7	2.603	1,650	.4974
20	672	+ 6	− 2	+ 3	− 3	+ 2	+ 5	− 3	− 3	− 6	2.395	1,609	.5094
30	720	+ 6	− 4	+ 5	....	− 1	....	− 2	− 1	− 4	2.193	1,579	.5226
40	785	+ 5	− 4	+ 4	− 3	− 2	+ 5	− 2	− 1	− 3	2.000	1,570	.5370
50	831	+ 3	− 4	+ 6	....	− 2	....	− 2	+ 1	− 1	1.821	1,513	.5525
60	886	+ 5	− 4	+ 6	− 4	− 3	0	− 2	0	+ 2	1.652	1,464	.5697
70	975	+ 9	− 4	+ 8	....	− 5	....	− 4	− 3	− 1	1.494	1,457	.5889
80	1,005	+ 5	+ 1	+ 6	− 4	+ 2	− 2	− 6	− 1	0	1.336	1,342	.6098
90	1,071	+ 5	− 5	+ 8	....	+ 3	....	− 9	− 2	− 1	1.182	1,266	.6333
100	1,124	+ 2	− 4	+ 6	− 7	+ 6	0	− 3	− 2	0	1.038	1,167	.6610
110	1,202	+ 3	− 4	+ 4	....	+ 3	....	− 4	− 3	0	0.905	1,088	.6925
120	1,276	+ 4	− 4	+ 5	− 5	+ 1	+ 4	− 4	0	0	.780	996	.7280
130	1,336	+ 1	0	0	....	0	....	− 1	+ 1	0	.664	887	.7690
140	1,396	+ 1	− 2	+ 1	− 3	0	+ 4	− 1	0	0	.558	779	.818
150	1,418	+ 3	− 2	0	....	+ 1	....	+ 2	− 1	+ 1	.464	658	.877
160	1,420	+ 1	− 1	− 2	+ 1	+ 2	− 1	0	− 1	+ 1	.381	541	.946
170	1,393	− 3	− 1	− 2	....	+ 3	....	+ 2	− 1	0	.320	446	1.034
180	1,307	0	− 1	− 1	+ 1	− 1	− 2	+ 2	− 1	0	.278	363	1.127
190	1,197	0	+ 1	− 1	....	− 1	....	− 1	+ 4	− 1	.247	296	1.239
200	1,011	− 2	+ 3	+ 1	0	+ 1	− 2	− 2	0	+ 1	.230	232	1.367
210	833	− 3	+ 6	− 1	....	0	....	0	0	− 1	.223	186	1.508
220	703	− 2	+ 3	0	+ 7	− 6	− 4	+ 3	0	− 2	.220	155	1.648
230	580	− 4	+ 8	− 1	....	0	....	+ 2	+ 2	− 6	.220	128	1.786
240	432	− 4	+12	+ 6	− 1	− 2	+ 2	+ 5	−11	− 8	.222	96	1.924
250	230	−10	+22	+ 4	....	− 6	....	−10	+ 4	− 2	.228	52	2.060
260	149	− 7	+21	+ 9	−16	− 5	+ 1	−16	+14	0	.238	35	2.196
270	107	−10	+25	+ 4	....	−14	....	−10	+ 7	− 2	.250	27	2.316
− 280	69	−16	+61	+10	−29	−22	0	−16	+19	− 1	.270	19	2.428
	[1]2.053	[2]+1.8	[2]−1.1	[2]−1.1	[2]−1.1	[2]+3.3	[2]+0.8	[2]−0.1	[2]−1.0	[2]−1.2	....	....	....

[1] Mean "solar constant." [2] Percentage deviations from mean "solar constant."

Table 16, for fixing the form of the solar spectrum energy curve outside the atmosphere, gives the numerical data from Mount Wilson observations, and is generally self-explanatory. The column headed $\frac{d\,\theta}{d\,\lambda}$ includes the multipliers proper for transforming the prismatic energy curve values given in column 2 to a normal scale as given in column 13. Columns 3 to 11 give percentage deviations of the individual determinations from the mean given in column 2. The mean of the values of the "solar constant" of radiation determined for the various dates is set down at the bottom of the table, together with the percentage deviations of the individual determinations therefrom, in order that the reader may see how far the divergencies of the prismatic curves are consistent with the view that there were actual variations of the "solar constant" of radiation, caused by variations of the transmission of the solar envelope. Such variations would principally affect the intensity of the rays of shorter wave-lengths and would tend to make the results corresponding to days of higher "solar-constant" values diverge above the others more and more toward the violet end of the spectrum. It will be found that seven of the nine series of observations are on the whole favorable to this view. Caution should be used in forming a judgment on this matter, however, because the results can not pretend to a high degree of accuracy in view of the difficulty and complexity of the process of obtaining them. Apart from the difficulty of correctly estimating atmospheric transmission, the irregular variations of the transparency of the sky during the tedious process of measuring the transmission of the spectroscope can not but have introduced error; and besides this, it is not certain that the deflections of the galvanometer are strictly proportional to the intensity of the light for the great range of deflections here involved. This point indeed ought to have been investigated, but as the determination of the exact form of the solar energy curve was regarded as a by-product, and not a main result of the work, it was neglected in view of the press of other matters.[1]

4. TEMPERATURE OF THE SUN.

The position of maximum energy in the solar spectrum as represented by the table and chart just given is rather indefinite, because there are in fact two maxima separated by the region of the G lines in the violet. The maximum would apparently be located at about 0.433μ if it were not for the powerful selective absorption of the sun's reversing layer at this point.

Employing the well-known formula of Wien for connecting the absolute temperature and position of maximum in the spectrum of the perfect radiator or "black body,"

$$\lambda_{max} T = \text{constant},$$

and taking the value of the constant as given by Paschen at 2,921, or as given by Lummer at 2,940, we obtain 6,750° or 6,790°, correspondingly, as the absolute temperature of the perfect radiator whose wave-length of maximum emission would

[1] The galvanometer used on Mount Wilson was almost exactly like the one used in Washington in all essential particulars. A test of the latter as regards proportionality of scale is given in Part III, Chapter II. There is there shown no departure of consequence from exact proportionality between current and deflection, for deflections not exceeding 15 cm., and only about 2 per cent at 25 cm. The range of deflections here in question very seldom reaches 25 cm.

agree with that of the sun. We shall not, however, conclude that this is the true temperature of the sun, for we know not how nearly the radiating surface of the sun approaches the condition of the perfect radiator; and certainly, as we receive the sun's rays, they have first come through the envelope surrounding the sun which appears to have modified very materially the form of the energy spectrum. Apparently this modification has been of a kind to diminish most strongly the shorter wave-lengths, and thus to increase the wave-length of maximum transmission above that of maximum emission. Accordingly, if the sun could otherwise be likened to a perfect radiator, we should infer from the evidence above given that its temperature probably exceeds the value 6,800° absolute. But there are some radiating substances, not "black bodies," for which the constant of Wien's formula does not exceed 2,600. If the sun is one of them, its temperature might be as low as 6,000°.

An estimate of the sun's temperature may also be made from the determination of the mean value of the "solar constant" combined with the well-known law of Stefan-Boltzmann connecting the temperature T and total radiation J of the perfect radiator:

$$J = \sigma T^4.$$

Employing the result of Kurlbaum, the constant σ is 76.8×10^{-12} gram calorie per square centimeter per minute. Let R_1=the radius of the sun and R_2= the mean distance from the sun to the earth. If now we call the mean value of the "solar constant" of radiation 2.1 calories, we have:

$$\frac{4 \pi R_1^2 \sigma T^4}{4 \pi R_2^2} = 2.1$$

Supplying the values R_1=695,500 km., R_2=149,480,000 km., and $\sigma = 76.8 \times 10^{-12}$ calorie, we find:

$$T = 5962°.$$

This value is also probably below the absolute temperature of the sun's radiating surface for similar reasons to those given above. The discrepancy between the values obtained by the two methods is not remarkable, in view of the uncertainty of the degree to which the radiating surface of the sun approaches the condition of the perfect radiator, and in view of the interposition of the selectively transmitting veil of the sun's envelope; for both of these considerations lead us to expect departures of the results from the true solar temperature, which might well be different with the two methods of determination.

5. NORMAL ENERGY CURVES OF THE SOLAR SPECTRUM AT MOUNT WILSON AND AT WASHINGTON FOR DIFFERENT ALTITUDES OF THE SUN.

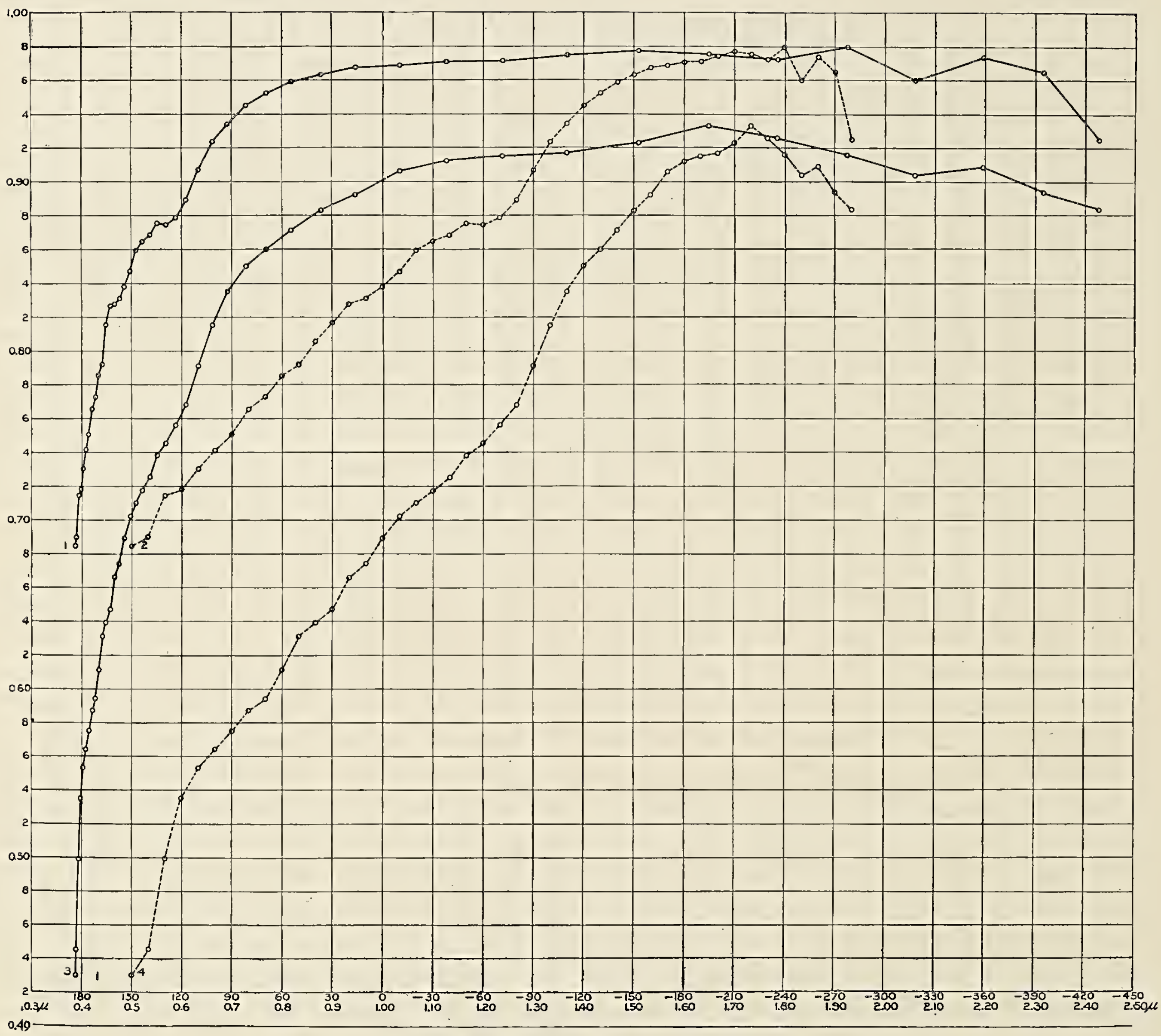
There is much variation in the transmission of the atmosphere for different apparently cloudless days, depending on the amount of haziness present; but it may serve some useful purpose to give what may be regarded as mean fair weather normal energy curves of the solar spectrum at Mount Wilson and at Washington, corresponding to different altitudes of the sun. These curves, shown in Plate XVI, have been obtained from the energy curve outside the atmosphere given in the preceding section 3 by aid of the mean transmission coefficients, which will be given under section 7 of the present chapter. No attempt is made to give solar absorption lines, and merely the positions of the water-vapor and larger oxygen bands are given. Plate XVI includes, besides the average normal energy curve of the solar radiation outside the atmosphere (line 6), the average normal energy curves at Mount Wilson and at Washington corresponding to air masses 1, 2, 3, 4, and 6 (see lines 5, 4, 3, 2, 1, and 11, 10, 9, 8, 7, respectively), which occur with the sun at the approximate zenith distances of 0°, 60°, 70°, 75°, and 80°, respectively. Mount Wilson determinations are given in full lines, and Washington ones in dotted lines in Plate XVI.

It is interesting to note, by comparison of the curves given, that the band of increased atmospheric absorption at about wave-length 0.60μ, entirely disappears outside the atmosphere, as it ought to do. This is evidence of the accuracy of the atmospheric transmission coefficients employed in computing the form of the solar energy curve outside the atmosphere. The large depressions between 0.40μ and 0.45μ, and between 0.50μ and 0.54μ are solar, and are caused by the many great absorption lines in the vicinity of G, *b*, and E of the solar spectrum.

6. THE MEAN VERTICAL TRANSMISSION OF THE ATMOSPHERE FOR THE TOTAL SOLAR RADIATION.

Formerly it was customary to treat the transmission of the atmosphere for the solar radiation as a whole, without considering the rays of different wave-length separately. Thus Pouillet, observing at Paris the change of the reading of his pyrheliometer attending changes in the sun's zenith distance, computed that for vertical transmission the solar beam reached the observing station with intensities ranging from 0.724 to 0.789 for different days, as compared with the intensity unity outside the atmosphere. Langley showed clearly that Pouillet's method gives too high values for the transmission, and that it is necessary to take account of the transmission of the rays of different wave-lengths separately. It is of interest to compare the results obtained at Washington and at Mount Wilson by the two methods.

Referring to Table 14, Chapter V, column 4 contains the values of the transmission obtained by Pouillet's method. For Washington the mean is 0.7866 and for Mount Wilson 0.8937. To obtain the true transmission values we must divide the pyrheliometer reading at the earth's surface, corresponding to zenith sun at mean solar distance, by the value of the "solar constant." Recalling that the pyrheliometer is never read at either of our observing stations with the sun actually



VERTICAL TRANSMISSION OF THE ATMOSPHERE.

in the zenith, it is necessary to determine this reading by a small extrapolation from values actually observed, and the best result of such an extrapolation is to be obtained by multiplying together columns 4 and 5 of Table 14. Accordingly, the product of these two columns divided by column 17 gives the true transmission for total solar radiation given in column 19 of Table 14. Its mean value for Washington is 0.701 and for Mount Wilson is 0.818. The ratio of the transmission, according to Pouillet's method, to the true transmission may be obtained by dividing column 17 by column 5 in Table 14, and this ratio will be found for each day of observation in column 18. The mean ratio for Washington is 1.124 and for Mount Wilson 1.093.

7. THE MEAN TRANSMISSIBILITY OF THE ATMOSPHERE ABOVE MOUNT WILSON AND ABOVE WASHINGTON FOR HOMOGENEOUS RAYS OF DIFFERENT WAVE-LENGTHS.

Atmospheric transmission coefficients for a few different wave-lengths have been given in Table 14. A table of mean transmission coefficients for Washington and Mount Wilson, respectively, including a large number of separate wave-lengths, will now be given.

It has been prepared by taking the mean of the results for each of the several wave-lengths as observed on twenty different days at each of the stations. These days have been selected over a wide range of time, including more than one year in each case (though the Mount Wilson values represent the conditions from May to October only), and chosen with the particular aim to represent fairly the different degrees of transparency observed. During each of the days included, the atmosphere remained apparently in a nearly uniform state of transparency. Many days occur, of course, when the sky is less transparent than during any represented here, for the results given show the conditions ordinarily found in cloudless weather. Large differences in transparency between different cloudless days are found both at Washington and on Mount Wilson, so that it has been thought worth while to give all the determinations of the separate days. If the reader will compare the results of the different days with the measurements of the pressure of aqueous vapor recorded in Table 14, and in Plate XVI, he will find no well-marked indication that the transparency at most wave-lengths depends on the pressure of water vapor.

The values included in the following Table 17 correspond to 44 different points in the spectrum, designated in the first and last columns of the table by differences of prismatic deviation, and by wave-lengths, respectively. There is given for each of these kinds of light the fractional amount of the original intensity of the ray which would remain after it had vertically traversed the atmosphere from its outer limit to the surface of the earth at Mount Wilson or at Washington, according to the individual and average results of twenty different days of observation. The mean values are plotted as functions of wave-lengths and of prismatic deviation, respectively, in Plate XVII.

Table 17.—*Vertical transmission of atmosphere.*

ABOVE MOUNT WILSON.

[Selective absorption in water-vapor bands not included.]

Prismatic deviation from F line.	1905.									
	June 14.	July 3.	July 25.	Aug. 3.	Aug. 9.	Aug. 14.	Sept. 14.	Sept. 27.	Oct. 10.	Oct. 18.
+150′	0.668	....	....	....	0.661	....	....	....	0.723	....
140	.728	....	0.692	0.631	.687	0.678	0.668	0.733	.711	0.676
130	.740	0.713	.656	.646	.698	.719	.734	.762	.708	.728
120	.745	.766	.705	.628	.692	.723	.743	.755	.748	.759
110	.751	.748	.695	.711	.698	.714	.767	.767	.755	.773
100	.766	.767	.710	.702	.714	.724	.767	.769	.769	.773
90	.770	.789	.705	.730	.719	.745	.759	.778	.767	.778
80	.778	.792	.726	.730	.741	.755	.769	.796	.785	.800
70	.793	.798	.733	.723	.741	.757	.778	.805	.811	.817
60	.798	.828	.752	.736	.753	.776	.813	.809	.820	.817
50	.804	.834	.740	.755	.738	.787	.807	.807	.817	.828
40	.816	.838	.767	.764	.766	.813	.824	.841	.840	.834
30	.839	.841	.780	.789	.783	.809	.836	.853	.847	.849
20	.846	.855	.787	.783	.798	.813	.849	.855	.849	.865
+10	.849	.865	.794	.807	.809	.824	.845	.865	.855	.863
00	.861	.875	.808	.807	.817	.834	.863	.861	.861	.877
−10	.869	.873	.807	.820	.830	.853	.859	.877	.867	.871
20	.877	.895	.829	.834	.830	.871	.873	.885	.887	.891
30	.889	.893	.836	.847	.838	.869	.871	.889	.887	.885
40	.887	.891	.838	.845	.847	.879	.877	.990	.895	.887
50	.893	.908	.848	.853	.855	.891	.879	.900	.900	.893
60	.892	.895	.843	.863	.861	.885	.877	.893	.897	.904
70	.900	.902	.850	.871	.840	.877	.881	.893	.897	.920
80	.908	.912	.856	.879	.865	.881	.897	.912	.910	.927
90	.920	.935	.865	.893	.881	.904	.914	.923	.931	.942
100	.945	.962	.887	.910	.895	.912	.933	.940	.942	.946
110	.958	.970	.910	.923	.916	.940	.953	.955	.946	.942
120	.965	.973	.925	.935	.931	.946	.955	.957	.962	.964
130	.967	.970	.938	.948	.940	.968	.955	.964	.962	.964
140	.975	.973	.946	.959	.951	.959	.968	.964	.980	.966
150	.972	.970	.944	.970	.955	.962	.976	.966	.966	.973
160	.981	.959	.954	.980	.957	.966	.973	.968	.991	.970
170	.981	.970	.960	.975	.968	.973	.968	.970	.986	.970
180	.977	.975	.959	.984	.966	.975	.973	.973	.977	.970
190	.986	.975	.957	.975	.970	.973	.977	.968	.975	.980
200	.989	.962	.966	.975	.977	.977	.977	.973	.993	(.991)
210	.993	.982	.965	.982	.973	.977	.982	.977	....	(.986)
220	.976	.982	.985	.980	.982	.973	.977	.977	.993	.986
230	....	.975	.972	.968	.991	.955	.982	.975	.991	.984
240	....	.980	.986	.966	.986	.973	.980	.989	.991	.993
250	(.980)	.964	.935	.966	.938	.944	.955	.982	.995	.968
260	(.983)?	.980	.971	.980	.962	.953	.967	.991	.989	.980
270	.968	.953	.953	.982	.929	.955	.964	.991	.989	.902
−280	.927	.959	.859	.975	.822	.887	.925	.942	.964	....

TABLE 17.—*Vertical transmission of atmosphere*—Continued.

ABOVE MOUNT WILSON.

[Selective absorption in water-vapor bands not included.]

1906.										Mean.	Wave-length.
May 16.	June 9.	June 19.	July 3.	July 17.	July 28.	Sept. 9.	Sept. 20.	Oct. 11.	Oct. 18.		μ
....	....	....	0.676	....	0.637	0.695	0.702	....	0.713	0.6844	0.387
....	....	0.698	.702	0.635	.667	.718	.671	0.711	.719	.6897	.390
....	0.697	.728	.686	.671	.665	.743	.711	.730	.736	.7090	.3942
0.646	.734	.730	.679	.710	.693	.738	.714	.719	.734	.7180	.3987
.678	.741	.730	.687	.716	.730	.741	.718	.724	.759	.7301	.4037
.703	.748	.757	.710	.726	.730	.753	.745	.730	.759	.7411	.4091
.728	.759	.766	.724	.731	.736	.748	.753	.745	.778	.7504	.4147
.721	.773	.778	.767	.757	.748	.774	.764	.760	.794	.7654	.4210
.716	.792	.807	.762	.769	.745	.774	.764	.764	.807	.7728	.4275
.733	.794	.804	.766	.773	.764	.796	.773	.776	.824	.7852	.4343
.748	.804	.802	.782	.792	.787	.805	.789	.785	.824	.7917	.4417
.759	.826	.822	.787	.791	.791	.809	.794	.789	.838	.8054	.4494
.762	.836	.826	.780	.807	.805	.813	.809	.817	.849	.8165	.4578
.759	.836	.861	.809	.809	.849	.834	.807	.820	.865	.8274	.4666
.773	.822	.843	.809	.817	.836	.843	.809	.817	.871	.8308	.4762
.771	.828	.847	.815	.817	.830	.849	.832	.826	.877	.8378	.4861
.776	.841	.855	.830	.838	.849	.859	.843	.836	.885	.8469	.4974
.789	.855	.869	.841	.843	.847	.863	.853	.855	.895	.8591	.5094
.803	.869	.877	.847	.855	.855	.871	.859	.855	.895	.8645	.5226
.811	.863	.881	.851	.853	.857	.877	.867	.859	.902	.8683	.5370
.824	.871	.887	.845	.869	.867	.875	.873	.865	.906	.8751	.5525
.838	.865	.881	.845	.859	.865	.875	.873	.863	.910	.8742	.5697
.838	.865	.883	.855	.875	.869	.887	.881	.875	.912	.8785	.5889
.838	.885	.895	.865	.871	.883	.902	.889	.881	.925	.8890	.6098
.865	.914	.908	.895	.893	.900	.908	.904	.910	.931	.9068	.6333
.871	.931	.927	.904	.940	.925	.929	.912	.916	.944	.9235	.6610
.873	.931	.946	.908	.942	.925	.938	.931	.923	.951	.9340	.6925
.893	.951	.948	.918	.957	.933	.944	.940	.931	.971	.9449	.7280
.914	.957	.959	.927	.951	.942	.948	.944	.940	.986	.9522	.7690
.916	.962	.959	.940	.962	.948	.953	.959	.946	.991	.9588	.818
.918	.984	.968	.948	.964	.959	.964	.959	.953	.991	.9631	.877
.927	.982	.973	.955	.959	.959	.968	.968	.962	.998	.9675	.946
.938	.984	.970	.953	.959	.964	.964	.968	.959	.995	.9687	1.034
.935	.989	.977	.959	.975	.966	.966	.970	.955	.991	.9706	1.127
.923	.984	.977	.962	.975	.966	.982	.970	.955	.993	.9711	1.239
.925	.975	.975	.970	.982	.968	.986	.968	.970	.993	.9746	1.367
.944	.975	.984	.970	.980	.980	.991	.977	.959	.995	.9775	1.508
.908	.968	.980	.989	.982	.957	.977	.984	.964	.993	.9756	1.648
.923	.982	.946	.980	.984	.942	.984	.986	.957	.998	.9724	1.786
.984	.977	.980	.991	.984	.946	.984	.986	.953	.991	.9800	1.924
.989	.942	.955	.935	.953	.933	.968	.951	.955	.991	.9600	2.060
.989	.946	.989	.955	.964	.968	.980	.984	.957	.993	.9740	2.196
.991	.977	.973	.970	.966	.948	.986	.964	.942	.995	.9649	2.316
.982	.933	.975	.877	.959	.818	.951	.940	.923	.959	.9251	2.428

TABLE 17.—*Vertical transmission of atmosphere*—Continued.

ABOVE WASHINGTON.

[Selective absorption in water-vapor bands not included.]

Prismatic deviation from F line.	1903.					1904.	1905.				
	Mar. 26.	Apr. 29.	July 7.	Aug. 24.	Oct. 29.	Oct. 21.	Jan. 26.	June 3.	Sept. 19.	Sept. 26.	Oct. 4.
+150′	0.409	0.400	0.344	....	0.532	0.462	0.427	0.483	0.438	....	....
140	.460	.415	.419	0.326	.530	.516	.468	.440	.476	....	0.507
130	.495	.430	.430	.370	.540	.556	.525	.448	.468	....	.631
120	.520	.440	.445	.400	.540	.585	.600	.451	.542	0.631	.643
110	.530	.450	.467	.436	.522	.600	.583	.460	.575	.618	.631
100	.542	.466	.496	.389	.540	.629	.603	.497	.611	.634	.617
90	.500	.450	.490	.566	.544	.665	.628	.485	.597	.667	.631
80	.556	.449	.494	.479	.564	.707	.631	.471	.659	.643	....
70	.561	.445	.500	.494	.564	.701	.646	.497	.690	.637	.617
60	.578	.445	.526	.466	.569	.716	.708	.564	.679	.655	.650
50	.575	.466	.570	.473	.586	.712	.700	.568	.721	.662	.646
40	.572	.486	.621	.515	.599	.738	.723	.538	.702	.695	.676
30	.575	.510	.603	.535	.586	.715	.731	.587	.702	.705	.690
20	.580	.543	.649	.522	.641	.702	.740	.587	.738	.743	.684
+10	.592	.535	.621	.476	.600	.735	.769	.570	.780	.750	.692
00	.606	.543	.608	.575	.605	.755	.771	.610	.809	.752	.725
−10	.615	.550	.631	.600	.640	.760	.771	.661	.791	.755	.743
20	.630	.560	.645	.590	.660	.773	.766	.618	.805	.769	.736
30	.642	.570	.660	.600	.680	.778	.785	.638	.813	.787	.740
40	.650	.590	.670	.620	.710	.790	.774	.660	.822	.787	.746
50	.661	.603	.646	.658	.731	.803	.807	.682	.783	.796	.750
60	.665	.620	.665	.670	.735	.814	.800	.711	.787	.798	.759
70	.661	.643	.671	.689	.743	.816	.782	.733	.805	.805	.776
80	.680	.660	.690	.690	.758	.845	.774	.752	.817	.805	.773
90	.710	.680	.710	.715	.775	.865	.796	.753	.873	.828	.771
100	.740	.690	.730	.740	.787	.890	.863	.775	.927	.863	.759
110	.765	.723	.767	.780	.795	.910	.840	.786	.933	.869	.811
120	.775	.730	.797	.800	.807	.915	.904	.800	.944	.869	.824
130	.790	.755	.815	.820	.817	.915	.887	.820	.914	.887	.826
140	.805	.765	.830	.843	.820	.920	.904	.838	.933	.897	.832
150	.810	.766	.842	.850	.830	.938	.904	.870	.942	.891	.851
160	.820	.790	.853	.860	.813	.945	.893	.890	.975	....	.863
170	.830	.808	.870	.870	.848	.955	.902	.918	.938	....	.873
180	.842	.820	.875	.875	.865	.963	.900	.925	.935	.887	.881
190	.855	.833	.875	.885	.883	.970	.904	.935	.935	.891	.881
200	.870	.855	.882	.900	.890	....	.897	.940	.933	.889	.885
210	.890	.870	.893	.902	.905	.893	.916	.968	.927	.910	.897
220	....	....	.885	.905	.915	....	.923	.940	.929	.891	.951
230	....	....	.873	.907	....	.970	.918	.910	.906	.935	.938
240	....	....	.860	.910	....	.930	.925	.890	.867	.877	.925
250	.920	.865	.850	.910	....	.937	.925	.890	.885	.902	.891
260	....	....	.847	.867	....	....	.951	.897	.887	.851	.885
270	....	....	....	....	....	....	.847	.897	.849	.841	.975
−280	....	....	....	....	....	....	.986	.897	.959	.900	....

TABLE 17.—*Vertical transmission of atmosphere*—Continued.

ABOVE WASHINGTON.

[Selective absorption in water-vapor bands not included.]

1905.		1906.				1907.			Mean.	Vertical transmission of 1 mile of air next sea-level.	Wave-length.
Nov. 1.	Dec. 4.	Feb. 15.	May 29.	Nov. 6.	Nov. 22.	Feb. 15.	May 13.	May 14.			
											μ
....	....	0.478	....	....	....	....	....	0.327	0.430	0.629	0.387
....	....	.447	0.284	....	0.579	....	0.389	.421	.445	.646	.390
....	....	.508	.347	....	.549	0.708	.513	.463	.499	.699	.3942
....	0.589	.492	.360	0.582	.567	.773	.544	.461	.535	.745	.3987
0.586	.601	.513	.483	.646	.615	.718	.556	.468	.553	.757	.4037
.575	.611	.542	.468	.646	.673	.728	.525	.492	.564	.761	.4091
.575	.604	.565	.510	.589	.668	.741	.522	.506	.575	.766	.4147
.581	.586	.603	.581	.617	.676	.785	.528	.547	.587	.767	.4210
.631	.598	.617	.583	.603	.714	.736	.522	.532	.594	.769	.4275
.652	.641	.615	.604	.589	.738	.734	.514	.573	.611	.778	.4343
.678	.641	.640	.622	.692	.759	.746	.570	.592	.631	.797	.4417
.655	.637	.628	.612	.733	.755	.766	.585	.537	.639	.794	4494
.670	.655	.640	.612	.698	.782	.782	.607	.552	.647	.793	.4578
.670	.664	.690	.634	.708	.782	.818	.627	.594	.666	.804	.4666
.681	.674	.718	.695	.684	.804	.836	.667	.597	.674	.811	.4762
.708	.697	.711	.736	.693	.793	.826	.673	.583	.689	.822	.4861
.710	.711	.714	.741	.684	.824	.837	.687	.619	.702	.829	.4974
.745	.718	.711	.769	.718	.822	.837	.676	.649	.710	.815	.5094
.746	.724	.736	.745	.702	.836	.845	.671	.650	.717	.830	.5226
.769	.726	.746	.734	.686	.843	.832	.664	.673	.725	.835	.5370
.780	.711	.764	.766	.759	.861	.843	.682	.705	.740	.843	.5525
.776	.708	.762	.771	.773	.861	.845	.690	.686	.745	.852	.5697
.783	.726	.782	.789	.815	.861	.863	.661	.711	.751	.860	.5889
.782	.733	.805	.818	.826	.871	.875	.711	.705	.768	.864	.6098
.807	.741	.811	.861	.843	.891	.875	.757	.755	.791	.872	.6333
.826	.760	.811	.883	.879	.893	.916	.807	.759	.815	.883	.6610
.865	.794	.845	.895	.897	.938	.899	.820	.773	.835	.894	.6925
.875	.817	.861	.897	.900	.933	.910	.838	.794	.850	.899	.7280
.893	.830	.885	.889	.927	.955	.925	.847	.802	.860	.903	.7690
.916	.849	.897	.891	.933	.942	.935	.849	.828	.871	.908	.818
.933	.879	.906	.904	.942	.951	.938	.881	.840	.883	.917	.877
.933	.893	.918	.900	.935	.957	.942	.908	.855	.892	.922	.946
.955	.916	.923	.920	.933	.968	.968	.935	.879	.906	.935	1.034
.962	.935	.916	.942	.925	.968	.957	.977	.883	.912	.939	1.127
.973	.923	.910	.948	.916	.977	.955	.938	.912	.915	.942	1.239
.955	.933	.916	.953	.925	.966	.951	.927	.953	.917	.941	1.367
.982	....	.942	.940	.923	.942	.955	.914	.977	.923	.945	1.508
.971	.962	.929	.927	.948	.955	.957	.889	.982	.933	.956	1.648
.964	.962	.912	.887	.959	.959	.948	.869	....	.926	.953	1.786
.938	.970	.912	.914	.953	.984	.902	.897	....	.916	.935	1.924
.959	.840	.871	.938	.962	.912	.929	.895	....	.904	.942	2.060
.962	.982	.867	.935	.938	.918	.933	.910	....	.909	.933	2.196
.916	.977	.863	.929	.938	.883	.925	.780	....	.894	.927	2.316
.798	.975	.830	.935	.948	.918	.908	.441	....	.875	.945	2.428

8. THE VERTICAL TRANSMISSION OF THE MILE OF AIR LYING NEAREST SEA-LEVEL.

In the next preceding section the mean vertical transmission of the whole atmosphere above Washington and that of the portion lying above the level of Mount Wilson have been given. By dividing the former by the latter we obtain the mean vertical transmission of the layer of air approximately 1 mile in thickness lying nearest the level of the sea, as given in the twenty-third line of Table 17 (Washington part). The weight of the column of air below the level of Mount Wilson is but little more than one-fifth of the weight of the column above it, but the far greater transparency of the upper air is shown by a comparison of column 22 of the Mount Wilson part with column 23 of the Washington part of Table 17, from which it appears that the atmosphere below the Mount Wilson level abstracts quite as much radiation as that above.

9. AN ABRIDGED PROCEDURE FOR DETERMINING APPROXIMATELY THE VALUE OF THE "SOLAR CONSTANT."

Pouillet assumed that the simple exponential formula of one term represented the varying transmission of the air for differing altitudes of the sun. Langley, following Radau, appreciated and acted upon the fact that the differing transmission of different spectral rays must be taken into account, so that in strict exactness there must be employed a formula which is the sum of an infinite number of exponential terms, each of which fits a single homogeneous ray of the complex solar beam. It is impossible to employ this ideal method and we have contented ourselves with a formula of more than forty terms, whose constants have been independently determined for every day of observation. In this way, as already stated, we have determined the values found in column 17 of Table 14. The values found in column 5 of the same table are determined by Pouillet's method, and the ratio of the two series is given in column 18.

Mr. Fowle called attention in 1905 to the approximate constancy of this ratio for Washington observations,[1] and he showed that the "solar-constant" values obtained at Washington by the spectrobolometric method differed little from the results which could be obtained by the following abridged method: Plot logarithms of pyrheliometer values as ordinates and secants of the sun's zenith distance as abscissæ. Choose the straight line most nearly representing the observations for values of secant z less than 2.5 and produce it to the point secant $z=0$. To the value of the pyrheliometer reading corresponding add 14 per cent and reduce to mean solar distance. The observations employed by Mr. Fowle were not reduced by the latest method, in which corrections for alteration of the sensitiveness of the bolometric apparatus have been introduced. Taking all the observations now

[1] Smithsonian Miscellaneous Collections, vol. 47, pt. 4, p. 399, 1905.

available, as given in Table 14, the average number which must be employed at Washington as a correcting factor, according to Mr. Fowle's method, is 12.4 per cent.

Applying the method of Pouillet to the observations made on Mount Wilson, it is found that the differences between the results obtained in this way and those obtained by the method of homogeneous rays vary from 4 to 13 per cent, as indicated by column 18 of Table 14. The variation of the differences is found to depend in some degree on the humidity of the air, and an approximate method for obtaining the "solar constant" applicable on Mount Wilson is the following: Proceed according to Mr. Fowle's method just given, excepting that for the additive term of 14 per cent substitute an additive term equal to 2.75 per cent plus as many per cent as there are millimeters in the average vapor pressure of water prevailing during the observations.

The average deviation of values obtained in this way from the values by the spectrobolometric method from observations made on Mount Wilson in 1906 is 1.5 per cent. No observations have been made on Mount Wilson during the winter months, so that it is not certain that the abridged method would be as satisfactory at all times.

10. THE OPTICAL QUALITY OF THE ATMOSPHERE ABOVE MOUNT WILSON.

Pyrheliometric observations of the solar radiation were made on Mount San Antonio in the latter part of August, 1905, by Mr. Ingersoll, simultaneously with complete pyrheliometric and bolometric observations for the determination of the "solar constant," made on Mount Wilson by Mr. Abbot. The station on Mount San Antonio is 3,050 meters high and that on Mount Wilson 1,780 meters high, so that the barometric readings at the two stations were approximately 540 and 625 mm., respectively. Mount San Antonio is in plain sight and only about 25 miles east of Mount Wilson, so that it is probable that the air above Mount San Antonio had nearly the same optical quality as that above an equal elevation over Mount Wilson. The observations were made to determine whether, for the rays not affected by the selective absorption of water vapor, the air between the two levels is of the same transmissibility as the average air above Mount Wilson; or, in other words, whether the dust and grosser parts of the air lie so nearly exclusively below the level of Mount Wilson that for the rays not much affected by the selective absorption of water vapor all layers above Mount Wilson may be supposed to have equal transmission for equal differences of barometric pressure.

Making the assumption of uniform optical quality for the air above Mount Wilson, we may introduce the barometric pressure as an exponent of the transmission formula. Let e_2, e_1, and e_0 be the intensity of a certain homogeneous ray on Mount Wilson, Mount San Antonio, and outside the atmosphere, respectively; a, the vertical transmission of the atmosphere above Mount Wilson; z, the sun's zenith distance; and B_2 and B_1, the barometric pressures at Mount Wilson and Mount San Antonio.

Then

$$\log e_2 = (\sec z) \log a + \log e_0$$

$$\log e_1 = \left(\frac{B_1}{B_2} \sec z \right) \log a + \log e_0$$

and

$$(\log e_1 - \log e_2) = \left\{ \frac{B_1}{B_2} - 1 \right\} (\sec z) \log a = 0.136 \ (\sec z) \log a.$$

By means of this expression the comparative intensities of the rays of the spectrum not affected by water vapor have been determined from the Mount Wilson spectrobolometric observations. For the remainder of the spectrum where water vapor is a powerful absorbent the formulæ for estimating its effect will be found in Part II of the present volume, and by the aid of these the probable intensity on Mount San Antonio of these selectively absorbed spectral regions has been estimated.

In this way the pyrheliometric readings which would be expected on Mount San Antonio have been computed from the observations made on Mount Wilson, and a comparison of them with the actually observed pyrheliometric readings on Mount San Antonio is given in the following table:

TABLE 18.—*Test of uniformity of optical quality of air above Mount Wilson.*

	Aug. 21, 1905, p. m.						Aug. 22, 1905, a. m.				
Secant z	1.33	1.46	1.64	1.93	2.37	2.98	3.17	2.42	1.47	1.31	1.08
Intensity observed: Wilson	1.461	1.439	1.403	1.348	1.283	1.202	1.286	1.385	1.517	1.539	1.645
Intensity observed: San Antonio	1.596	1.566	1.540	1.489	1.428	1.352	1.433	1.527	1.642	1.667	1.675
Intensity computed, San Antonio	1.568	1.542	1.506	1.449	1.385	1.323	1.392	1.491	1.591	1.610	1.633
Observed−computed	.028	.024	.034	.040	.043	.029	.041	.036	.051	.057	.042

It appears from the results just given that the values computed fall, without exception, below the values observed on Mount San Antonio. It is possible that the decrease in the absorption of water vapor may have been greater than has been allowed for in the computation, and it is also possible that the pyrheliometer used upon Mount San Antonio may have read slightly higher there than on Mount Wilson as a consequence of the difference in air pressure. Either of these sources of error would tend to diminish the departures; but, on the whole, it is believed to be more likely that the difference between the results of computation and observation is caused by the continued increase of the purity of the air for optical purposes, even above the level of Mount Wilson.

As hitherto explained, this conclusion does not invalidate the accuracy of the "solar-constant" values determined from observations at Mount Wilson or even lower levels, provided the atmosphere may be considered as composed of parallel shells, each by itself of uniform transparency over a limited area, but which may differ in any manner in transparency from shell to shell.

Chapter VII.

THE CAUSES OF DISAGREEMENT BETWEEN "SOLAR-CONSTANT" DETERMINATIONS OF DIFFERENT OBSERVERS.

It can not be expected that our estimate of 2.1 calories, as the mean value of the "solar constant" of radiation based on the numerous determinations given in Chapter V of Part I of this volume, will be generally accepted as the most probable value of this quantity, despite the confirmatory evidence based on the temperature of the earth, which will be furnished in Part II, unless the causes of the disagreement between this value and those heretofore determined and published by able observers are satisfactorily explained.

1. PYRHELIOMETRY.

A part of the discrepancy of "solar-constant" measurements is due to the discordance of the pyrheliometric or actinometric apparatus used by different observers. Although the matter is fundamental, observers have not always published the data showing how their readings were reduced to so-called "calories," and only infrequently do we find recorded comparisons between instruments of different types. Generally each observer has contented himself with one instrument or two instruments of a single type. From a theoretical point of view every kind of actinometer or pyrheliometer is defective in which the rays are absorbed upon an exterior or front surface and their effect determined by temperature measurements behind or within, and this class includes all types except that of Michelson and that described in the present volume. Observers have seldom determined the effects, if any, of different velocities of the wind, different inclinations of the instrument to the horizontal plane, or different barometric pressures; and never, until the experiments described in the present volume, were any means used for measuring a known quantity of heat to see if the apparatus actually recorded as supposed.

K. Ångström in his report of his observations upon Teneriffe,[1] after citing numerous actinometric observations of other observers at high stations, remarks:

> It would seem that a subject which has attracted so much attention as is witnessed by all these researches, and which has been treated by eminent observers, would be fairly exhausted; but this is not the case. The cause of it is, first, that the old forms of actinometers and pyrheliometers are defective, so that their results are not comparable with one another, and therefore have but a limited value; and, secondly, the climatological conditions in which these observations have been made have been rarely favorable.

[1] Nova Acta Regiae Societatis Scientiarum Upsaliensis, series 3, vol. 20, fasc. 1, 1901.

Ångström has himself been active in attempting to remedy this deplorable disagreement of the instruments used for measuring radiation, and his own electrical compensation pyrheliometer has come into general use, and was adopted provisionally as a standard instrument at the international solar conference at Oxford in 1905. Nevertheless these instruments are also defective in theory,[1] and different samples disagree in practice, and there is no means of checking their indications by determining with them known quantities of heat.

It is almost certain that there is a disputable ground of 25 per cent in the pyrheliometric and actinometric measures of the last 30 years, and if we consider only those of the present time, there is still believed to be an uncertainty of 10 per cent as between the observations of one observer and another, due entirely to the lack of standardized pyrheliometers or actinometers.[2] Happily this condition of affairs will probably be soon remedied in the present advanced state of laboratory practice.

2. ESTIMATION OF THE TRANSMISSION OF THE ATMOSPHERE FOR SOLAR RADIATION.

Prior to Langley's observations upon Mount Whitney, there had been numerous attempts to determine the "solar constant," which are well summed up in the excellent little book of Radau, entitled "Actinometrie."[3] It is shown that nearly all observers excepting Violle[4] were in comparative agreement so far as their actual observations go, and if the transmission of radiation by the atmosphere be estimated by the simple formula $I = Ap^{\epsilon}$, which was employed by Pouillet and many others, the value of the "solar constant" would be found in the neighborhood of 1.75 calories.

But Forbes, Violle, Crova, and others showed convincingly that this simple equation does not accurately express the diminution of radiation attending the decline of the sun from zenith to horizon, or the descent of the observer from a

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[1] Though the electrically heated strip loses heat at the back as fast as the other, it certainly does not from the front, because one strip is heated from within and the other from in front. The discrepancy must in some degree depend on the air pressure, the wind, and the inclination to the vertical.

[2] See Chwolson "Über den Gegenwärtigen Zustand der Actinometrie," Repertorium für Meteorologie, Kaiserlichen Akademie der Wissenschaften, St. Petersburg, 1892.

It may be stated also that by the aid of Mr. H. H. Kimball and Mr. L. R. Ingersoll, indirect comparisons have been made between the new standard pyrheliometer of this observatory and six different Ångström electrical compensation pyrheliometers in possession of the United States Weather Bureau and of the University of Wisconsin, and these comparisons have showed differences of from 9 to 15 per cent, depending on which Ångström pyrheliometer was being compared. The latest type of Ångström instrument, with manganin strips, is in closer agreement with our own instruments than the older ones, and reads about 9 per cent lower than ours. See also the comparison between the Ångström-Chwolson compensation actinometer and the Ångström electrical compensation pyrheliometer, given in the publication "Sur la marche annuelle de l'intensite du rayonnement solaire a Varsovie," by Ladislas Gorczynski, 1906, p. 89.

[3] Actinometrie par M. R. Radau. Gauthier-Villars, Paris, 1877.

[4] Langley pointed out on page 74 of his report of the Mount Whitney Expedition, that the water equivalent of Violle's actinometer as stated by Violle appears to be nearly 25 per cent greater than its linear dimensions, which Violle gives, would warrant. If, in fact, there was an error of this magnitude in the constant of Violle's instrument, his measurements of solar radiation after correction would come within reasonable distance of those of other observers.

high altitude to a lower one. Accordingly, several different empirical formulæ of more complexity were proposed, which, owing to their more numerous constants, could be made to fit the observed variation of the total intensity of radiation under different conditions more closely. By the aid of such empirical formulæ higher values of the "solar constant" have been obtained, and some of these in our own time have even gone as high as 4 calories!

The tendency toward high values of the "solar constant" was powerfully stimulated by the publication of the report of the Mount Whitney Expedition by Langley in 1884. As Radau had stated,[1] so Langley emphasized and acted upon the fact that the formula $I = Ap^{e}$ applies only to a homogeneous bundle of rays, and the intensity of solar radiation outside the atmosphere can be exactly determined only when the atmospheric transmission coefficients of the rays of all wave-lengths which go to make up the complex beam of the sun are separately determined and allowed for. Langley was the first to determine and apply atmospheric transmission coefficients for numerous rays of different wave-lengths in the solar spectrum. He found it impracticable to determine the transmission coefficients in the water-vapor bands of the infra-red, but assuming that there were no water-vapor bands in the solar spectrum outside our atmosphere, he avoided this difficulty by smoothing the spectrum energy curve which he determined for the limit of the atmosphere so as to leave no water-vapor bands at all. Had Langley stopped with these steps accomplished, he would have left us as the result of the Mount Whitney expedition 2.060 calories, the mean value as determined by high and low sun observations at Lone Pine, or 2.220 calories, the mean value similarly determined from observations at Mountain Camp.[2] But by the train of reasoning on pages 142–144 of his report, and contradicting the train of reasoning on pages 145–147, he convinced himself that the formula $I = Ap^{e}$ does not hold for the earth's atmosphere even for a strictly homogeneous ray. He therefore altered his results by two different procedures, one of which, he states, was of a kind to give too low a value of the "solar constant" and the other too high. By this means he obtained the values 2.630 and 3.505. The mean of these, 3.068, or in round numbers 3.0 calories, he adopted as the "solar constant."

But in fact both procedures were calculated to give too high results, and the most probable result of Langley's observations lies below either of them, and is in fact 2.22 or 2.06 calories, according as the work at Lone Pine or Mountain Camp is regarded as the better.[3] In order to recognize this, it is necessary to examine the argument which led him to doubt the accuracy of the formula $I = Ap^{e}$ as applied to the transmission of homogeneous rays through the earth's atmosphere.

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[1] Actinometrie, p. 23.

[2] See report of Mount Whitney Expedition, p. 148, columns 1 to 5, inclusive.

[3] Very, in Monthly Weather Review, vol. 29, p. 362, has combined Langley's observations with Rayleigh's theory of the diffuse reflection of the sky, assuming certain constants apparently arbitrarily, and has thereby arrived at values near 3.1 calories. This method seems to be inconclusive.

For this purpose consider lines 26 to 43 of page 144 of the Mount Whitney report, which detail the precise method employed in obtaining what Langley regarded as a minimum value, namely, 2.63 calories:

We now proceed to determine from our bolometer observations a value which we may believe from considerations analogous to those just presented to be a *minimum* of the "solar constant," and one within the probable truth. All the evidence we possess shows, as we have already stated, that the atmosphere grows more transmissible as we ascend, or that for equal weights of air the transmissibility increases (and probably continuously) as we go up higher. In finding our minimum value we proceed as follows, still dealing with rays which are as approximately homogenous as we can experimentally obtain them: Let us take one of these rays as an example, and let it be the one whose wave-length is 0.6μ and which caused a deflection at Lone Pine of 201. The coefficient of transmission for this ray, as determined by high and low sun at Lone Pine and referred to the vertical air mass between Lone Pine and Mountain Camp, is 0.976. From the observations at Lone Pine, then, the heat of this ray upon the mountain should have been

$$201 \times \frac{1000}{976} = 206.0$$

but the heat in this ray actually observed on the mountain was 249.7. Therefore, multiplying the value for the energy of this ray outside the atmosphere calculated from Mountain Camp high and low sun observations (275) by the ratio $\frac{2497}{2060}$ we have 333.3, where 333.3 represents the energy in this ray outside the atmosphere as determined by this second process. In like manner we proceed to deal with the rays already used, thus forming column 8 in Table 120.

It is evident that the transmission coefficient determined for the wave-length $0.6\ \mu$ by the aid of high and low sun observations at Lone Pine represented the mean transmission of a ray of this wave-length through a mass of air containing all the kinds of strata between Lone Pine and the limit of the atmosphere. Such a transmission coefficient would certainly be greater than that which would have been found if the air had all been like that between Lone Pine and Mountain Camp, because the lower layers are least transparent. Therefore the value 0.976 could be known *a priori* not to represent the transmission of the air between Lone Pine and Mountain Camp, but to be certainly greater than the true transmission coefficient for the air between these stations. Accordingly the discrepancy between the computed and observed intensities at Mountain Camp is only what should be expected, and implies no failure of the formula $I = Ap^{e}$ at all; for that formula was used in the computation of the intensity at Mountain Camp, just quoted, with a coefficient p, which was certainly wrong. Indeed, the same demonstration given by Langley on page 146, and which, regarding the earth's atmosphere as made up of superposed parallel layers of unequal transparency, proves the probable accuracy of this exponential formula $I = Ap^{e}$ as a means of estimating from high and low sun observations at the earth's surface the intensity of a homogeneous ray *outside the atmosphere*, can also be made to show that for a medium composed of parallel layers of unequal transparency there is no means of computing the intensity at any point whatever *within the medium.*[1] In other

[1] See Chapter I of Part I of these Annals.

words, under those conditions it is a formula of extrapolation, not of interpolation. Accordingly, by introducing a multiplier determined by this misleading computation, too high a value of the "solar constant" was obtained by Langley. The argument on which he acted may be stated in a plausible form as follows: If Bouguer's exponential formula with the transmission coefficient obtained by high and low sun observations at Lone Pine gives too low a value of the intensity of homogeneous solar radiation for a station within the atmosphere like Mountain Camp, as was shown by actual observation, much more will it give too low a value outside the atmosphere. An equally plausible and equally fallacious argument is the following: It is said that the density of water decreases with increasing temperature at the mean rate of about 0.00041 per degree from 0° to 100°, but observations at 4° prove that water is actually denser at this temperature than at 0°, therefore the supposed decreased density at 100° is a delusion!

Owing to this most unfortunate error, the great authority of Langley has supported the value 3.0 calories for the last twenty-five years, and many observers have been perhaps wrongly influenced by it. In reality Langley's Mount Whitney observations support the value 2.1 calories, and the difference between 2.06 and 2.22, found at Lone Pine and Mountain Camp, respectively, is no more than the roughness of the spectrobolometric work would lead us to expect.

It is now almost universally recognized that all procedures for determining the "solar constant," excepting that which depends upon determining atmospheric transmission coefficients for many wave-lengths of the spectrum, are mere empirical extrapolations without theoretical basis. Numerous empirical formulæ have been proposed and applied from time to time in connection with actinometric observations. Particular stress is often laid by their authors on the importance of allowing for water-vapor absorption, so that one is lead to think that the differences between numbers of the order of 1.9 calories, as actually observed at elevations of nearly 5,000 meters, and 3 calories or more, their proposed values for the "solar constant," are attributed by many to the presence of the trifling amount of water vapor which exists above these high levels. This seems preposterous when it is recalled that the principal water-vapor bands lie in a part of the spectrum where only a small fraction of the energy of the sun is found. The reader may examine in this connection Plate XVI, which shows the energy spectrum as extrapolated to the limit of the atmosphere by the transmission coefficients determined by means of homogeneous rays on Mount Wilson, or if he doubts the correctness of the extrapolated form he may consider also the theoretical energy curve of a "black body" of the apparent temperature of the sun (about 6,000°) as computed according to Planck's formula.

It is found comparatively easy to make a variety of the empirical formulæ fit pyrheliometer observations at high and low sun, or even at high and low altitudes; but it is entirely another thing to admit the accuracy of extrapolation to zero atmosphere by means of them. K. Ångström in 1890 most unfortunately applied an empirical formula to combine observations of his own and those of Langley on Mount Whitney, with a view to allow for the supposed absorption of carbon dioxide on incoming solar radiation.[1] He had no difficulty in fitting his new formula to the observations; and extrapolating thereby to the limit of the atmosphere, published his still quoted value of the "solar constant," 4.0 calories. The progress of investigation in the next decade convinced him that solar radiation is little affected by the absorption of carbon dioxide, and in 1900 he withdrew the above-mentioned value.[2] Nevertheless, although withdrawn and discountenanced by its author, Ångström's value, 4.0 calories, is still being quoted.

Ångström omitted to state any value of the "solar constant" in discussing his important observations on Teneriffe, and his remarks are well worthy of the attention of those who are still employing empirical formulæ to compute "solar constants" from actinometric observations alone. After showing that his results at all elevations and all air masses were well represented by an empirical formula of five constants, he remarks:[3]

> As I have already said, I place little value (Je ne fais pas grand cas) upon an empirical formula of this kind. I have not employed the method of Least Squares in its calculation, for it would be more work than the result is worth. * * *
>
> Neither these observations nor our empirical formulæ are able to inform us as to the behavior of the radiation above the limit of observation, and it is only by making observations at more considerable elevations, as well as by spectrobolometric researches, that we shall be able to arrive at some clearness upon this subject.

Despite the fact that empirical formulæ with several constants may be made to fit actinometric observations within the limit of error of observation, no dependence whatever can be placed upon extrapolations to zero air mass by means of them. For the result depends on the form of the expression used, and it would even be possible to find a formula which would give any desired value of radiation at zero air mass between the limits plus and minus infinity and still fit the actinometric observations with considerable success. The result of extrapolation depends even on the air mass from which the extrapolation is made, as shown in a most instructive fashion by a table of Hansky, who observed on Mont Blanc in 1900.[4] He employed apparatus of Crova's design and extrapolated by means of Crova's formula. The means of assuring himself that the results are expressed in calories

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[1] Annalen der Physik und Chemie, 39, pp. 267–311, 1890.
[2] Annalen der Physik, 3, p. 721, 1900.
[3] Nova Acta Regiæ Societatis Scientiarum Upsaliensis, series 3, vol. 20, fasc. 1, 1901.
[4] Comptes rendus, 140, p. 425, 1905.

and the separate observations at different air masses are not stated. On July 24, 25, and 26, 1900, he obtained maximum values on the summit of Mont Blanc with the sun near the meridian of 1.81, 1.72, and 1.78 "calories," respectively, but he did not regard these days of observation as satisfactory. On September 4 and 5, 1900, he obtained maxima of 2.02 and 1.99 "calories." The barometric pressure was 423–427 mm., and the pressure of aqueous vapor only from 0.1 to 0.3 mm. Hansky's extrapolations to the limit of the atmosphere are given from various air masses, as follows:

m.	1	2	3	4	5	6	7
Sept. 4, a. m.	2.76	2.97	3.29	....	....	....	....
Sept. 4, p. m.	2.49	2.66	2.57	3.11	3.22	3.08	....
Sept. 5, p. m.	2.52	2.48	2.80	2.92	3.45	2.96	3.19

The mean of these values (which have a range of about 34 per cent around the mean value) is 2.90, but Hansky prefers 3.29 for this curious reason:

Comme dans ces déterminations ce sont les maxima qui sont plus probable, on peut considérer 3.29 calories comme la quantité qui se rapproche le plus de la vraie valeur de la constante solaire.

Le nombre 3.45 calories a été obtenu pour une hauteur trop faible du soleil (9° au-dessus de l'horizon du Mont Blanc) pour être accepté.

He also says of the "solar constant:" "Il est presque certain qu'elle est comprise entre 3.0 calories et 3.5 calories et que, en tout cas, elle est superieure à 2.54 calories, nombre donne dernierement par M. Langley." The number 2.54 here referred to is "a provisional preliminary value" published in 1903 by Mr. Langley, which was recomputed and republished by him in 1904 as 2.19,[1] and owing to a slight correction to the constant of the actinometer appears as 2.15 in the present volume.

If there be any propriety in applying the conclusions from spectrobolometric observations of homogeneous rays, as conducted upon mountains of 1,800 meters and 3,500 meters height, to estimate what addition to Hansky's noon actinometric readings of September 4, 1900, would most probably represent the result of passing from the summit of Mont Blanc to the limit of the atmosphere, this addition would be estimated at not exceeding 10 per cent; and the most probable result to be derived from Hansky's observations would seem to us to be that the "solar constant" did not, on September 4, 1900, exceed 2.22 "calories."

Stankewitch,[2] in a journey to the Pamir, made several observations with an Ångström electrical compensation pyrheliometer. The maximum readings obtained at altitudes exceeding 4,000 meters and with the sun at about 16° from the zenith, were 2.01 and 2.02 "calories." From these readings, combined

[1] See Astrophysical Journal, XVII, 97, 1903; and XIX, 315, 1904.

[2] Comptes rendus, 131, p. 879, 1900.

with others made at zenith distances of about 38°, he computes by the formula $I=Ap^{\frac{1}{\sin z}}$ "solar constants" of 2.56 and 2.74, respectively. It would require more than two points, determined at air masses of 1.04 and 1.27, respectively, to justify an extrapolation to air mass 0.00, so that this apparent support to the higher values of the "solar constant" is of little weight.

SUMMARY.

The principal reasons why our new mean value of the "solar constant," namely, 2.1 calories, differs widely from some other published values, are two:

First, the measurements of the intensity of solar radiation at the earth's surface made by different observers are not comparable, because there is no common or international scale of exact pyrheliometry; and generally there are no exact means even of comparing one observer's work at one time and place with what he has done at another time and place. The differences attributable to these defects of apparatus are believed to range over 25 per cent in the last thirty years, and over 10 per cent at the present time.

Second, as stated in 1877 by Radau, there is only one method of estimating the transmission of the atmosphere which seems to be sound in theory, and that method requires spectrum observations. This method has been employed to determine the "solar constant" at Washington, Lone Pine, Mount Wilson, and Mount Whitney, at sea-level, 940 meters, 1,800 meters, and 3,500 meters, and the results obtained are in close agreement, do not vary with the altitude of observation, and give a mean value of the "solar constant" of 2.1 calories. Determinations by other methods, depending on observations of total radiation combined with extrapolation by empirical formulæ of different kinds, vary all the way from 1.75 to 4.0 calories, because the means of observation have been inadequate, according to theory, and the inadequacy can not be supplied by devising empirical formulæ, or by treating the results by the method of Least Squares.

PART II.

RADIATION AND TERRESTRIAL TEMPERATURE.

INTRODUCTION.

DEPENDENCE OF TERRESTRIAL TEMPERATURE ON SOLAR RADIATION.

Neglecting minor factors, the temperature of the earth's surface depends chiefly upon the amount of radiation the earth receives from the sun. It appears probable that there has been no great progressive change of the amount of solar radiation in historic times, because there seems to be no record which would indicate a considerable change of the earth's climate. On the other hand, there have occasionally been periods of generally higher or lower temperatures over large areas of the earth's surface and of several years' duration, which may perhaps be ascribed either to temporary fluctuations in the amount of solar radiation available to warm the earth or to changes in the amount of radiation emitted by the earth (as a planet) to space. On account of the peculiar functions of the atmosphere it is possible that changes of available solar radiation may occur independently of a change in the radiation of the sun itself; and it is also possible for the radiating power of the earth (as a planet) to fluctuate for the same reason, so that different temperatures of the earth's surface may be consistent with equal rates of loss of its heat to space. Accordingly the study of the relations of terrestrial temperature and solar radiation is very complex, and involves not only the knowledge of the value of the "solar constant" of radiation and the law of dependence of radiation and temperature for a body of the temperature and material of the earth's surface, but also a knowledge of the reflecting and absorbing power of the atmospheric constituents and of the earth's surface for solar radiation and the reflecting, convecting, absorbing, and radiating powers of the atmosphere which are involved in the escape of terrestrial radiation. At present the progress of investigation is far from reaching that satisfactory degree of knowledge of all these particulars which the science of meteorology demands; but some conclusions appear to be warranted in view of facts already published and additional ones included in the present volume.

Chapter I.

THE EFFECT OF THE ATMOSPHERE ON THE DIRECT BEAM OF THE SUN.

It is necessary to distinguish between the transmission of the atmosphere for solar rays (which lie almost wholly between wave-lengths 0.37μ and 2.5μ) and the transmission for terrestrial radiation, which is almost wholly of greater wave-length than 2.5μ.

As regards the transmission of solar rays, there are two kinds of hindrance exercised by the atmosphere. In the first place there is a general scattering of the rays, which is greatest at the violet end of the spectrum, and at Washington at zenith sun is nearly 50 per cent at a wave-length of 0.4μ, but less than 10 per cent at a wave-length of 1.6μ. It is by no means to be inferred that the decrease of the intensity of the direct beam of the sun caused by this scattering of light implies a real loss of the radiation available to warm the earth in anything like these proportions. As will be shown more particularly in the chapter on Sky Radiation, a considerable fraction of the light lost from the direct beam reaches the surface of the earth indirectly from the sky. Furthermore, the principal amount of scattering occurs near the surface of the earth; for, as shown by the Mount Wilson observations, the loss of light in the direct beam for zenith sun at an elevation of about 1 mile above sea-level is only about 27 per cent at a wave-length of 0.4μ, and only 2 per cent at a wave-length of 1.6μ, so that in the direct beam at zenith sun about half the loss of violet light due to scattering by the air occurs within a mile of the earth's surface, and for infra-red rays of a wave-length 1.6μ, no less than three-fourths.

THE AMOUNT OF RADIATION TRANSMITTED BY THE (DRY) ATMOSPHERE.

In order to estimate the whole amount of light in the direct solar beam which reaches the earth's surface at any given time, it is necessary to take account of the different thicknesses of air traversed by the beam in reaching the earth's surface more and more remotely from the subsolar point. For the purposes of this inquiry the projection of the earth upon a plane may be divided into concentric rings, whose inner and outer radii are given in the following table. Each of these rings is reached by solar rays following a path of air whose length as compared with that for zenith sun will be designated m. The average amounts of different rays received at the level of Mount Wilson and sea-level, respectively, have been estimated from Mount Wilson and Washington observations[1] by using Pouillet's exponential formula and applying a graphical summation.

TABLE 19.—*Direct solar radiation reaching the earth (clouds and water vapor neglected).*

Radii of rings.	Proportion of area πR^2.	Air masses m.	Average transmission Mount Wilson.							Average transmission Washington.						
			Wave-length μ.							Wave-length μ.						
			0.4	0.5	0.6	0.8	1.0	1.2	1.6	0.4	0.5	0.6	0.8	1.0	1.2	1.6
0 –0	....	1.0	0.731	0.850	0.901	0.957	0.970	0.977	0.981	0.512	0.652	0.701	0.823	0.870	0.892	0.918
0 –.643	....	1.0 – 1.31	.70	.83	.89	.95	.97	.97	.98	.47	.62	.67	.80	.85	.88	.91
.643–.866	....	1.31– 2.00	.62	.78	.85	.93	.96	.97	.98	.35	.51	.58	.74	.80	.83	.87
.866–.940	....	2.00– 2.90	.48	.68	.78	.93	.93	.94	.96	.21	.36	.44	.63	.72	.76	.81
.940–.985	....	2.90– 5.57	.30	.53	.67	.84	.90	.91	.93	.08	.20	.26	.47	.59	.64	.71
.985–1.000	....	5.57–35.5	.05	.20	.34	.62	.70	.79	.81	.00	.02	.08	.14	.22	.29	.39

Fraction of amount of solar radiation directed toward the whole earth received on each of the rings of surface above mentioned (clouds and water vapor neglected).

			Mount Wilson level.							Washington level.						
0 –0.643	0.412	....	0.28	0.34	0.37	0.39	0.40	0.40	0.40	0.19	0.25	0.28	0.33	0.35	0.36	.37
.643–.866	.336	....	.21	.26	.29	.31	.32	.33	.33	.12	.17	.19	.25	.27	.28	.29
.866–.940	.133	....	.06	.09	.10	.12	.12	.13	.13	.03	.05	.06	.08	.10	.10	.11
.940–.985	.087	....	.03	.05	.06	.07	.08	.08	08	.01	.02	.02	.04	.05	.06	.06
.985–1.000	.032	....	.00	.01	.01	.02	.02	.02	.03	.00	.00	.00	.00	.01	.01	.01
Total..	1.000	....	.58	.75	.83	.91	.94	.96	.97	.35	.49	.55	.70	.78	.81	.84

The last line gives the direct radiation reaching the levels mentioned over the whole earth for different wave-lengths, as compared with the radiation of the same wave-lengths outside the atmosphere (clouds neglected).

The solar spectrum outside the earth's atmosphere may be apportioned between different wave-lengths as follows:

Wave-lengths.

μ..............	0–0.45	0.45–0.55	0.55–0.67	0.67–0.90	0.90–1.10	1.10–1.40	1.40–∞
Proportion......	0.12	0.20	0.17	0.20	0.11	0.08	0.12

Multiplying the totals given on the last line of Table 19 by the appropriate numbers among those just given, and adding up the results for the entire spectrum, we find that the amounts of sunlight of all wave-lengths included within a cylinder whose base is the cross section of the earth, and measured at the limit of the atmosphere, the level of Mount Wilson, and sea-level, respectively, would be in the ratios

[1] The values of transmission coefficients employed differ slightly from those given in Tables 14 and 17 of Part I, because computed before the completion of those tables and collected from other data. The difference in the case of Mount Wilson values is slight, but in case of Washington the values used in what follows are several per cent lower than the mean of the values given in Part I; but it is thought possible that the values used in what follows are actually more representative of average conditions than the ones given in Part I, as the latter were obtained exclusively on excellent days.

of 100 to 84 to 62, if it were not for clouds and the additional selective absorption of water vapor, which will now be estimated.

THE AMOUNT OF DIRECT SOLAR RADIATION ABSORBED BY WATER VAPOR.

As explained in Chapter III of Part I, the bolographic observations at Mount Wilson and at Washington are sufficient to give, in comparable terms, the total radiation outside the atmosphere, the total radiation which actually reaches the observing station, and the total radiation which would reach the observing station if there were no selective absorption of water vapor like that in and near the great infra-red regions $\rho\sigma\tau$, Φ, Ψ, and Ω, so that by subtraction the value to be assigned for the absorption produced by water may be computed. Although no very accurate result can be expected, an attempt has been made to derive an empirical formula for connecting the amount of direct solar radiation absorbed by water vapor with the amount of water vapor present in the atmosphere.

The latter quantity is of course an uncertain factor in the matter, but Hann in his "Meteorologie," pages 224–226, gives data for the following approximate empirical relations: Let e_o, e_w, and e_f be the pressures of aqueous vapor in centimeters at sea-level, on a mountain, and in free air, the two latter stations being of height h meters above sea-level.

Then

$$e_w = e_o 10^{-\frac{h}{65000}}$$

and

$$e_f = e_o 10^{-\frac{h}{6000}\left(1+\frac{h}{20000}\right)}$$

When $h=1,800$, as for Mount Wilson, then,

$$e_w = 0.53 e_o \quad \text{(A)}$$

$$e_f = 0.47 e_o \quad \text{(B)}$$

Let Q=the total amount of water vapor in the atmosphere below the level h expressed in terms of the weight of vapor in grams per square centimeter area, or, what is practically the same, the number of centimeters in depth to which the earth's surface would be covered by liquid water if the aqueous vapor in the atmosphere were precipitated.

Then

$$Q = 2.3 e_o \left(1 - 10^{-\frac{h}{5000}}\right)$$

Whence from sea-level to the limit of the atmosphere

$$Q_o = 2.3\ e_o \quad \text{(C)}$$

and above a level of 1,800 meters

$$Q_w = 2.3\ e_o\ (.44) = 4.4\ Q_o$$

Substituting in the last expression $e_w=0.53\ e_o$

$$Q_w = 1.9\ e_w \quad \text{(D)}$$

By the aid of the expressions (C) and (D) and after considerable experimenting with the data observed at Mount Wilson and Washington, the following formulæ have been obtained. Let F represent the fraction of the total solar radiation outside the atmosphere which the absorption of water vapor abstracts; Q the amount of water vapor as determined by formula (C) or (D); *m* the air mass as heretofore employed. Two formulæ, (E_1) and (E_2), differing only by a small amount in the constant term have been obtained for Mount Wilson and Washington, respectively. The difference is probably caused by the fact that owing to the general "absorption" being greater above Washington than above Mount Wilson, there is less radiation available to be absorbed by water vapor above Washington.

$$F_w = (5.7 + 1.2\ Q_w m) \text{ per cent} \qquad (E_1)$$

$$F_o = (5.1 + 1.2\ Q_o m) \text{ per cent} \qquad (E_2)$$

It is clear that these empirical formulæ can not represent the absorption for exceedingly small quantities of precipitable water in the atmosphere, because if $Q=0$ it is nearly certainthat $F=0$, and not 5.7 or 5.1, as given by the formulæ. But for all values of Q which have been met with in the Washington and Mount Wilson observations the formula holds fairly well, and it is believed that it will answer for the purpose to which it will be put in what follows.

From the following summary the reader can see what degree of success has been reached in trying to represent the absorption of water vapor by these formulae:

TABLE 20.—*Absorption of water vapor.*

Mount Wilson.	M.	e_w.	Per cent absorption. Observed.	Per cent absorption. Computed.	O-C.	
1906.						
July 24	1.65	1.13	10.9	10.0	+0.9	
28	1.43	.80	8.7	8.3	+ .4	
31	1.38	.78	6.3	8.1	−1.8	
August 3	1.41	.52	6.7	7.4	− .7	
4	1.45	.70	7.8	8.0	− .2	
14	1.14	.97	9.3	8.2	+1.1	
14	1.28	.97	9.0	8.5	+ .5	
14	1.44	.93	9.3	8.8	+ .5	
14	1.67	.85	9.3	8.9	+ .4	+0.35
14	2.30	.85	10.5	10.2	+ .3	
14	2.58	.87	10.1	10.8	− .7	
15	1.38	.80	9.8	8.2	+1.6	
15	1.50	.76	9.8	8.3	+1.5	
15	2.32	.71	10.7	9.5	+1.2	
15	2.60	.70	10.5	9.8	+ .7	+1.00
15	2.96	.68	11.0	10.3	+ .7	
15	3.40	.68	11.3	11.0	+ .3	
17	1.72	1.08	10.0	9.9	+ .1	
21	1.74	.50	6.0	7.7	−1.7	
September 9	1.38	.94	7.2	8.6	−1.4	
18	1.42	.38	6.2	6.9	− .7	
25	1.34	.52	7.7	7.3	+ .4	
October 2	1.33	.64	8.4	7.6	+ .8	
4	1.29	.28	6.8	6.5	+ .3	
4	1.36	.27	6.2	6.5	− .3	
4	1.46	.29	7.3	6.7	+ .6	
4	1.61	.28	6.8	6.7	+ .1	
4	1.83	.27	7.6	6.8	+ .8	+0.35
4	2.11	.26	7.5	6.9	+ .6	
4	3.14	.24	7.9	7.5	+ .4	
4	4.11	.22	8.1	7.8	+ .3	
9	1.41	.26	6.5	6.5	.0	
13	1.44	.25	7.8	6.5	+1.3	
Mean					.76	

Washington.	M.	e_o.	Per cent absorption. Observed.	Per cent absorption. Computed.	O-C.	
1903.						
February 19	1.58	0.07	3.7	5.4	−1.7	
1905.						
January 26	2.08	.08	4.4	5.6	−1.2	
September 26	1.37	.46	8.3	6.8	+1.5	
October 4	1.63	.73	9.9	8.4	+1.5	
November 1	1.89	.40	7.1	7.2	− .1	
December 4	2.36	.21	5.8	6.5	− .7	
1906.						
May 29	1.11	.98	7.0	8.1	−1.1	
November 22	2.11	.48	8.3	7.9	+ .4	
1907.						
February 15	1.73	.21	6.6	6.1	+ .5	
15	1.80	.21	6.4	6.1	+ .3	
15	1.87	.21	6.6	6.1	+ .5	
15	1.95	.22	6.6	6.2	+ .4	
15	2.06	.22	7.0	6.3	+ .7	
15	2.20	.22	6.9	6.5	+ .4	+0.3
15	2.36	.23	6.9	6.6	+ .3	
15	2.60	.23	7.2	6.8	+ .4	
15	2.85	.23	6.9	6.9	.0	
15	3.18	.22	7.0	7.0	.0	
15	3.53	.22	7.1	7.2	− .1	
May 13	1.40	.91	9.0	8.6	+ .4	
14	1.24	1.19	8.8	9.2	− .4	
14	1.29	1.22	9.3	9.4	− .1	
14	1.34	1.23	9.2	9.6	− .4	
14	1.40	1.21	9.3	9.8	− .5	
14	1.47	1.19	9.4	9.9	− .5	−0.8
14	1.56	1.19	9.5	10.2	− .7	
14	1.65	1.15	9.8	10.3	− .5	
14	1.75	1.11	9.3	10.5	−1.2	
14	1.89	1.14	9.7	11.2	−1.5	
14	2.02	1.16	9.6	11.6	−2.0	
Mean					.88	

We come next to apply the results thus far obtained to determine the water-vapor absorption over the whole earth.

From the data collected by Arrhenius, as quoted by Hann,[1] the distribution of water vapor and temperature over the earth is approximately as follows. The

[1] Meteorologie, p. 228.

fourth and fifth lines have been added here and are computed from the second and third:

Table 21.—*Terrestrial distribution of water vapor and temperature.*

Latitude	0°–20°	20°–30°	30°–40°	40°–50°	50°–60°	60°–(90°)
Temperature (centigrade)	24°.8	20°.8	14°.9	8°.7	1°.6	(−7°.0)
Water vapor at earth's surface. Grams per cubic meter (yearly mean)	17.8	13.5	9.8	7.0	4.7	(3.1)
Sea-level:						
Vapor pressure e_o	1.87	1.35	0.96	0.70	0.43	(0.26)
Precipitable water Q_o	4.3	3.1	2.2	1.6	1.0	(0.6)
Mount Wilson level:						
Vapor pressure e_w	1.00	0.74	0.56	0.39	0.22	(0.17)
Precipitable water Q_w	1.9	1.4	1.0	0.7	0.4	(0.3)

In order to take into account both change of air mass and change of water vapor, the projection of the earth's surface upon a plane, as viewed from the sun, may be divided into smaller areas by a series of concentric circles, and these again subdivided by projecting upon them the parallels of latitude as situated at the times of the equinoxes. The areas included in this distribution are indicated in the following table:

Table 22.—*Projected areas of the earth's surface.*

Average air mass	1.20	1.65	2.45	4.25	20	Total.
Radii	0–0.643	0.643–0.866	0.866–0.940	0.940–0.985	0.985–1.000	
Latitude.	Areas.					
0°–20°	0.264	0.102	0.033	0.019	0.007	0.425
20–30	.098	.056	.017	.009	.003	.183
30–40	.050	.071	.018	.011	.003	.153
40–50		.075	.023	.011	.003	.112
50–60		.033	.024	.012	.004	.073
60–70			.020	.018	.004	.042
70–90				.008	.003	.011
Total	.412	.337	.135	.088	.027	.999

By combining the data of Tables 20, 21, and 22 with formulæ (C), (D), and (E), the amounts of water-vapor absorption have been computed. The results will be expressed in two ways, as follows: Firstly, regarding the total amount of solar radiation directed toward the whole earth as unity, the fractions thereof absorbed by water vapor, independent of, and additional to, the scattering of the solar rays by the dry atmosphere, are summed up in the table for the several latitude belts under the caption A. Secondly, regarding the total amount of solar radiation directed toward a given belt of latitude as unity, the fractions thereof absorbed by water vapor, interpreted in the above sense, appear under the caption B.

TABLE 23.—*Percentage absorption of water vapor.*

Altitude.	Above 1,800 meter-level.[1]							Above sea-level.[2]						
Latitude.	0° to 20°	20° to 30°	30° to 40°	40° to 50°	50° to 60°	60° to 70°	70° to 90°	0° to 20°	20° to 30°	30° to 40°	40° to 50°	50° to 60°	60° to 70°	70° to 90°
A	4.22	1.64	1.26	0.88	0.54	0.31	0.10	5.89	2.28	1.61	1.12	0.67	0.37	0.11
B	9.9	9.0	8.2	7.9	7.4	7.4	9.1	13.9	12.5	10.5	10.0	9.2	8.8	10.0

[1] Total A, 8.95 per cent; average B, 8.4 per cent.
[2] Total A, 12.05 per cent; average B, 10.7 per cent.

Regarding the accuracy of this estimate of water-vapor absorption, it is probable that the results are a little too large; for the data included by Arrhenius in estimating the amount of water vapor at different latitudes is based on observations of both cloudy and fair days, whereas direct sunlight is received only when the sky is not overcast. This consideration affects the results at sea-level more than it does those for the 1,800 meter level; because cloudiness is far less prevalent at the higher level, and the observational data upon which the formulæ for the relative amounts of water vapor at different levels are based, represent average and not exclusively fair weather conditions.

Applying the results just obtained to correct those representing the transmission of the dry atmosphere, given on an earlier page, it is found that the direct solar radiation available to the whole earth and reaching the limit of the atmosphere, the 1,800 meter level and the sea-level, respectively, would stand in the ratio of 100 to 75 to 50 if it were not for the presence of clouds.

15000—08——10

THE EFFECT OF CLOUDINESS ON THE DIRECT RADIATION OF THE SUN.

FREQUENCY OF CLOUDS.

The first four columns of the following table are from the results collected by Arrhenius.[1] The remaining columns will be explained below.

TABLE 24.—*Frequency of clouds.*

Latitude.	Percentage cloudiness.		Percentage area, continent.	Percentage average cloudiness.	Projected area of zone.	Percentage of sunlight intercepted by clouds.
	Continent.	Ocean.				
+90°– 70°	....	....	....	60?	.0055	0.3
70 – 60	58.1	66.7	72.1	60.5	.021	1.3
60 – 50	56.3	67.6	55.8	61.3	.037	2.3
50 – 40	45.7	63.3	52.9	54.0	.056	3.0
40 – 30	36.5	52.5	42.9	45.7	.076	3.5
30 – 20	28.5	47.2	38.8	40.0	.092	3.7
20 – 10	28.5	47.0	24.2	42.5	.104	4.4
+10 – 0	50.1	56.7	23.3	55.2	.108	6.0
— 0 – 10	54.8	59.7	24.2	58.5	.108	6.3
10 – 20	47.8	54.0	22.5	52.6	.104	5.5
20 – 30	29.6	49.6	23.3	44.9	.092	4.1
30 – 40	38.9	51.0	12.5	49.5	.076	3.8
40 – 50	62.0	61.1	2.5	61.1	.056	3.4
50 – 60	71.0	71.5	0.9	71.5	.037	2.6
−60 – 90	....	....	....	70?	.027	1.9
Total	....	....	....	....	....	52.1

RADIATION INTERCEPTED BY CLOUDS.

Although, as will be shown in the next chapter, the clouds appear not to reflect above a third of the solar radiation away, they prevent a much larger quantity from actually reaching the earth's surface in the direct solar beam. There is practically no direct solar radiation transmitted through clouds, with the exception of the gauziest cirri. Accordingly it is proper to subtract from the amount of direct sunlight all that is intercepted by clouds, and this is the same as the percentage cloudiness given for the different zones in column 5 of Table 24; for the whole earth the corresponding quantity is obtained by a summation of the column 7, which is the product of columns 5 and 6, and is 52 per cent. This result could be interpreted as meaning that on the average 52 per cent of the earth's surface is obscured by clouds all the time, in which case it would be necessary to inquire which parts of the earth are thus obscured. But it is believed to be sufficiently exact at the present stage of knowledge to say, rather, that on the average all parts of the earth are obscured 52 per cent of the time.

[1] London, Edinburgh, and Dublin Philosophical Magazine, series 5, vol. 41, p. 275, 1896.

FINAL ESTIMATE OF THE EFFECT OF THE ATMOSPHERE ON THE AMOUNT OF DIRECT SOLAR RADIATION.

We may now finish our estimate of that portion of the direct sun rays which reaches sea-level; for we may assume that during 52 per cent of the time there is none, owing to the clouds, and during 48 per cent of the time, which is clear, there is 50 per cent transmitted, as stated on an earlier page, so that on the average there appears to be but 24 per cent of the direct solar radiation which reaches sea-level. This estimate depends of course on the assumption that the transparency of Washington sky is fairly representative of sea-level conditions during clear weather.

In order to estimate the proportion of the solar radiation which reaches the Mount Wilson level in the direct beam, it would be necessary to know the average cloudiness over the earth for that level, and this is not accurately known. Hann gives [1] data for several land stations from which we draw the conclusion that not far from 35 per cent of the clouds are found below a 2,000-meter level. It seems probable that if the subject could be investigated thoroughly over the ocean regions a larger proportion of the clouds would be found at the lower levels than the observations made at the few land stations, on which the above result is based, would indicate.[2] It will therefore be assumed here that 60 per cent of the clouds are found above the Mount Wilson level, so that the earth may be supposed to be (0.6 by 52 or) 31 per cent of the time cloudy at the Mount Wilson level. During the remaining 69 per cent of the time when the sky is supposed clear, 75 per cent of the solar radiation over the whole earth reaches this level in the direct beam, as stated on a previous page, so that on the average 52 per cent of the radiation of the sun comes directly to the level of Mount Wilson.

Finally we conclude that the average amounts of the direct solar radiation reaching the limit of the atmosphere, the 1,800-meter level, and sea-level, respectively, as summed up in preceding pages for the whole earth, stand in the ratio of 100 to 52 to 24.

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[1] Hann's Meteorologie, p. 274.

[2] The measurements given by Hann indicate the proportion of clouds observed whose lower surface is beneath the levels specified. We are here, of course, interested in the level of the upper surface of the clouds, but we make the assumption that the low clouds here in question are not very thick, so that Hann's figures for the lower surfaces apply roughly to the upper ones as well.

Chapter II.

THE REFLECTING POWER OF CLOUDS.

Owing to the high reflecting power and frequent occurrence of clouds, they produce a considerable reduction of the amount of solar radiation available to warm the earth. In the next preceding chapter we have considered the effect of clouds to diminish the amount of solar radiation which reaches the surface of the earth in the direct beam, and now we propose to investigate the proportion of the amount intercepted by the clouds which is diffusely reflected to space and thereby lost to the earth. Very few, if any, observations have been made hitherto for determining the reflecting power of clouds, so that most writers who have occasion to mention it compare their reflection to that of white paper, or some other white solid, and estimate it at about 75 per cent.[1]

APPARATUS EMPLOYED FOR MEASURING CLOUD REFLECTION.

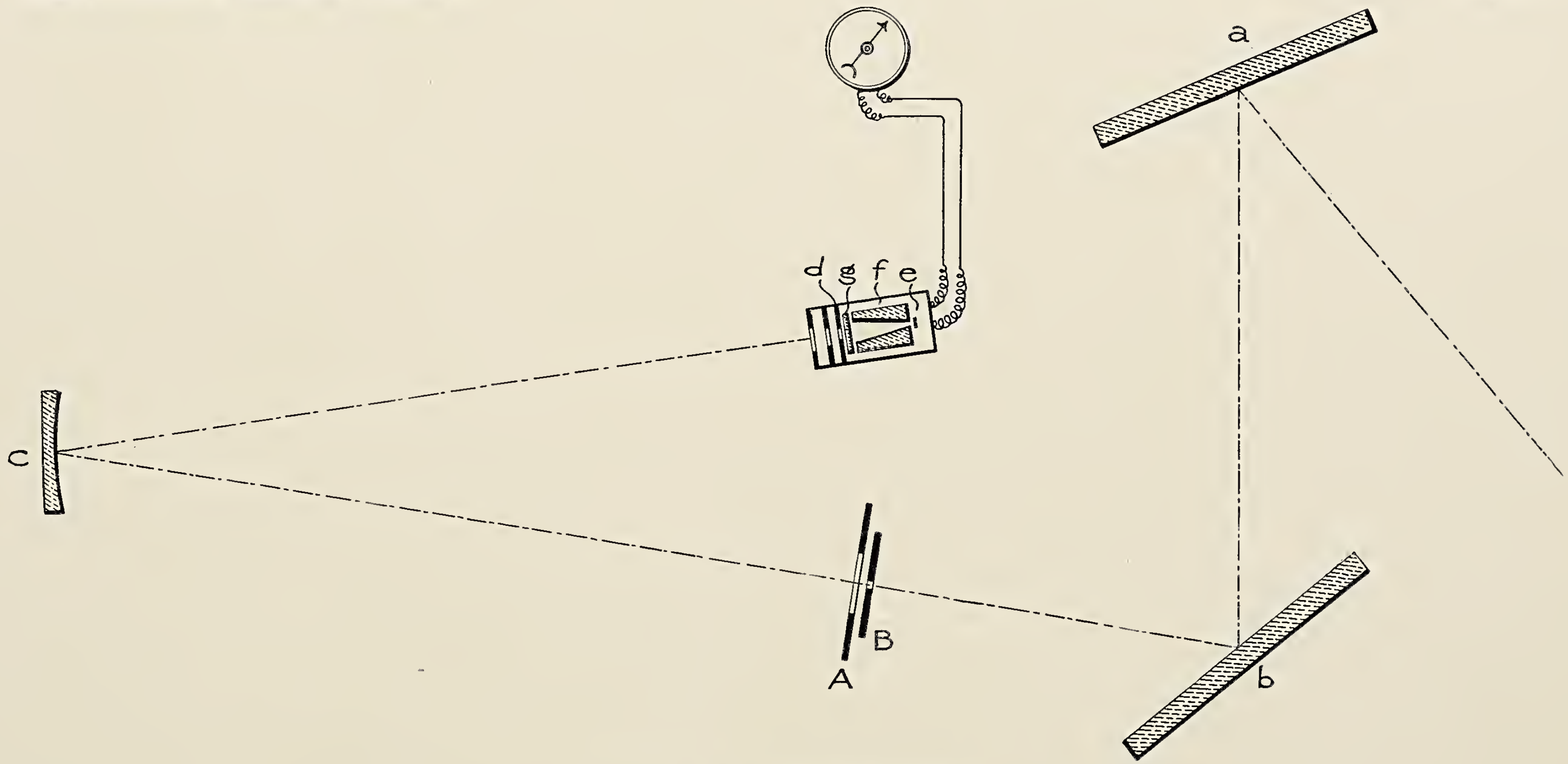
In 1906 the subject of cloud and sky radiation measurements was taken up by the Smithsonian expedition,[2] and there was erected on Mount Wilson a tower about 50 feet high, standing on a point overlooking the junction of two deep canyons, so that instruments could be pointed downward on three sides of the tower within 20° of the vertical, and still have a deep field of view. These canyons were occasionally nearly filled up to the base of the tower by a level-topped sea of cloud, as shown in the illustration, Plate XVIII.

On this tower was placed a bolometric outfit, as illustrated by the accompanying diagram (Pl. XIX). The plane mirror *a*, 15 inches in diameter, was mounted free to rotate about a horizontal north and south axis, and also about trunnions at right angles to this, so that the mirror was adapted to reflect light vertically downward upon a second plane mirror *b*. Both mirrors were provided with graduated circles and with coarse and fine adjustments of position, so that the data required for determining the angular position of the reflected rays could be observed. From the second mirror the rays were reflected to a concave mirror *c*, of 1 meter

[1] See S. Arrhenius, London, Edinburgh and Dublin Philosophical Magazine, series 5, vol. 41, p. 256, 1896. Also H. H. Kimball, Monthly Weather Report, vol. 29, p. 210, 1901.

[2] This work was much aided by Professor Hale's staff; in the erection of the tower by Mr. Ellerman, and in actual observing by Messrs. Palmer and Olmsted.

Cloud Sea, Mount Wilson.



Apparatus for Cloud-reflection Work.

focus, which was focussed upon a diaphragm *d* having a circular aperture about 1 centimeter in diameter. Beyond this was a bolometer strip *e*, 1 centimeter in height and 1.2 millimeters in width, toward which pointed a ray cone (by Brashear) composed of four wedge-shaped silvered mirrors, two of which are indicated at *f* of Plate XIX, and adapted to compress the cone of rays coming from the mirror, so that all rays which passed through the diaphragm fell directly or by reflection upon the surface of the bolometer. Between the diaphragm *d* and the ray cone *f* was a glass plate *g*, whose purpose was to cut off the rays of great wave-length emitted by the bolometer and by the clouds.

The purpose of the concave mirror, the diaphragm, and the ray cone thus combined, was to gather a sufficiently intense beam of rays for accurate bolometric observations, and at the same time to collect all these rays from an angular area substantially equal to that of the sun. It was proposed to reflect to the bolometer alternately the image of the sun and the image of an approximately equal angular area of clouds or sky, and thus to compare the heating effect of direct and diffusely reflected solar radiation.

A great difficulty of the research was found to be the provision of means for diminishing the intensity of the direct solar rays in an accurately known ratio, so as to be comparable with the intensity of the diffusely reflected rays from the clouds or sky. Since the reduction factor required is between 50,000 and 100,000, it is not practicable merely to insert a single diaphragm of measured area to cut down the aperture of the cancave mirror; for the diameter of such a diaphragm would be too small for accurate measurement. Neither is it satisfactory to depend to any great extent on a shunt or series resistance in the galvanometer circuit, for this presupposes that the bolometer deflections are proportional to the intensity of radiation received, independent of whether the intensity of radiation is great or small, an assumption which is in some degree erroneous when a large rise of temperature is involved.

The means adopted after many experiments were these: Between the concave mirror *c* and the plane mirror *b* there was inserted a diaphragm, called "A," of a large, rectangular, measured aperture, and this limited the beam when cloud or sky radiation was in question. Upon this diaphragm were fixed accurate catches for holding a second diaphragm, "B," having a smaller rectangular aperture about 11×1.2 centimeters. Upon this in turn could be placed either of several very thin diaphragms, "C," "D," "E," "F," each having five knife-edged circular apertures in a vertical row, and there were provided little shutters for closing either or all of these holes at pleasure. The four sets of holes progressively diminished in area, so that a single hole of the diaphragm "F" was only about $\frac{1}{10000}$ the size of the aperture "A."

To measure the effects of the several diaphragms, direct linear measurements were made of the apertures in diaphragms "A," "B," and "C;" but as a slight inequality of action of the ray cone was discovered, it was necessary to observe the bolometric effect of light through different parts of the diaphragm "A," in order to compute and allow for the unequal effectiveness of rays coming to the bolometer from different angles. The comparative effect of the remaining diaphragms was obtained in the following manner: By inserting 2,000 ohms resistance in series with the galvanometer it was possible to observe the bolometric effect of the sun rays admitted through one hole of the diaphragm "C." In this way the effectiveness of the five several holes of the diaphragm "C" was tested under comparable conditions, and from the results the effective area of the central hole, "C_3", was computed in terms of the total area of all five. There was then placed before the hole "C_3" a rotating disk (called "H") from which was cut a sector, measuring 0.0450 of a circle. This reduced the sunlight to nearly the same intensity as the diaphragm "F_3", and by inserting 50 ohms in the galvanometer circuit it was possible to measure the comparative bolometric effects of the light through "F_3", and through "C_3" and "H." In actual comparisons the sunlight observed through "F_3" was found to be so much more intense than the cloud light through "A" as to require 50 ohms in series with the galvanometer when the sunlight was observed, while only 1 ohm remained in series during the sky and cloud measurements. Accordingly additional measurements were needed to compare the sensitiveness of the bolometric apparatus under these two conditions. Such measurements were made by the aid of another rotating disk ("G") having a sector measuring 0.187 of a circle.

The following table gives the results of the various determinations above mentioned:

Measurements of sectors G and H on graduated circle of theodolite.

Sector.	Angular width.					Mean.	Mean 360°.
	° ′	° ′	° ′	° ′	° ′	° ′	
G........	67 19	67 15	67 25	67 18	67 18	67 19	0.1870
H........	16 9	16 15	16 19	16 8	16 12	16 12.6	0.0450

DETERMINATION OF THE EFFECT OF DIAPHRAGMS USED FOR CLOUD-REFLECTION WORK.

Diaphragm A. Aperture, 11.60×6.40 cm. Area, 74.2 sq. cm.

Diaphragm B. Aperture, 10.80×1.25 cm. Area, 13.50 sq. cm.

Correction factor for effectiveness of aperture including vertical section at center of A as compared with average effectiveness over entire aperture of A=0.982.

Reduction factor for $B=\frac{74.2}{13.50}\times 0.982=5.40$.

Diaphragm C, five holes each 0.800 cm. diameter. Total area, 2.513 sq. cm.

Correction factor for effectiveness of hole C_3 as compared with average effectiveness of all five holes, 0.983.

Reduction factor for $C_3 = \frac{74.2}{2.513} \times 5 \times 0.982 \times 0.983 = 147.7$.

Disk H. Aperture 0.0450 of complete circle.

Reduction factor for $C_3H = 3{,}282$.

Comparative effectiveness of C_3H and F_3 observed by deflection method at different times:

Deflection C_3H	41.79	41.19	36.59	36.24
Deflection F_3	17.22	16.82	14.85	14.90
Ratio	2.43	2.45	2.47	2.43

Check upon the accuracy of the deflection method for lights of small intensity:

Deflection E_3	43.75	43.55	43.25
Deflection E_3G	8.36	8.09	7.98
Ratio	.1912	.1859	.1845

Aperture G, by deflection method, 0.187; by angular measurement, 0.1870.

Reduction factor for $F_3 = 3{,}282 \times 2.445 = 8{,}020$.

Disk G. Aperture 0.1870 of complete circle.

Comparative effectiveness of bolometer with 50 ohms and 1 ohm in galvanometer circuit as observed at different times:

Deflection E_3 50Ω	47.7	48.4	43.52
Deflection E_3G 1Ω	51.6	54.3	47.72
Ratio	.924	.892	.912

Reduction factor for F_3, 50 Ω compared with

$$A,\ 1\ \Omega = \frac{8020}{0.1870} \times \frac{1}{0.909} = 47{,}200$$

Angular semidiameter of bolometer diaphragm as viewed from concave mirror = 0.00556.

1906.	Sun's semidiameter.	Ratio solid angles of sun and diaphragm.	Reduction factor (column 3÷47,200).
	$''$		
August 22	951	0.687	1.456×10^{-5}
September 8	955	.693	1.469×10^{-5}
September 13	956	.694	1.471×10^{-5}
October 19	966	.708	1.500×10^{-5}

OBSERVATIONS OF CLOUD REFLECTION.

It was unfortunately not until August, 1906, that the apparatus for determining the reflection of clouds was sufficiently perfected for good observations. Prior to that time measurements had indeed been made on several days, but there were no means of accurately comparing the intensity of the sun radiation observed in the direct beam with that diffusely scattered. It was not until August 22 that a fog came sufficiently high to make observations worth while, and on that day a large number of measurements were made.

The following are sample observations:

[August 22, 1906. Observers, C. G. A. and L. R. I.]

Object observed.	Circle readings.		Diaphragm and series resistance.	Watch time a. m.	Scale reading, radiation.		Deflection.
	Large.	Small.			On.	Off.	
	°	°		h. m.			
Cloud	218	0	A 1Ω	6 32	4.3	25.2	20.9
					4.1	26.7	22.6
Sun	234	356	F_3 50Ω	6 35	12.5	28.8	16.3
					12.8	28.9	16.1

In contrast to the previous year, the autumn of 1906 presented few opportunities for cloud observations, and it was only on September 13, 1906, that a few additional measurements were made. This time the fog was very high, and about fifteen minutes after observations were concluded it covered the mountain completely and prevented all further work of the kind. No other opportunities for cloud observations occurred during the stay of the expedition. The results of the two days, August 22 and September 13, are very concordant, but they constitute only a fragment of the evidence required for a full treatment of the subject of the reflecting power of clouds, and are sufficient only for a preliminary estimate. It is hoped to continue and extend the research. In the following table is given: (1) The zenith distance of the sun; (2) the nadir distance of the observed cloud; (3) the azimuth of the cloud (without regard to sign) measured from the azimuth of the sun as zero; (4) the ratio of intensity of radiation from cloud and from direct sun for equal angular areas.

Table 25.—*Observations of cloud reflection.*

Sun's zenith distance.	Cloud's nadir distance.	Cloud's azimuth.	Radiation $\frac{\text{Cloud}}{\text{Sun}} \times 10^7$.
Observed August 22, 1906.			
°	°	°	
77	89	7	288
	89	20	267
76	86	93	30
	87	179	45
	74	7	191
74	86	21	188
	90	20	231
73	72	38	71
	82	92	35
72	88	92	35
71	90	15	251
70	87	5	253
	88	171	47
69	87	76	45
	78	8	186
68	88	35	136
67	85	2	257
	82	90	39
66	89	38	130
65	83	144	49
	89	165	53
	82	24	144
52	86	130	53
	81	8	142
51	83	17	142
Observed August 22, 1906—Continued.			
°	°	°	
	87	163	65
	88	165	57
	89	45	81
50	90	26	118
49	89	1	140
	81	26	111
43	84	29	85
	87	3	122
42	84	25	104
	88	69	57
	87	68	67
	86	68	69
41	84	68	71
	78	67	65
40	85	141	59
Observed September 13, 1906.			
30	88	0	39(?)
	70	0	104
	62	1	92
	54	2	70
	89	22	78
	58	4	75
	38	4	62
	20	9	51
	90	83	65

The observations have been separated into several groups according to the zenith distance of the sun, and in each of these groups subgroupings were formed according to nadir distance of the cloud. It was then seen at once that the cloud surface departed more and more from the character of a perfect "matt surface" the greater the zenith distance of the sun and the greater the nadir distance of the cloud. In order to study this characteristic, the results were plotted with the ordinates of the curves proportional to the observed cloud radiation, and the abscissæ representing the azimuths of the observed parts of the cloud. With each curve was given the solar zenith distance and cloud nadir distance at the time of observation. Apart from minor irregularities it was found that the observations supported each other very well; and, while showing how large a proportion of the diffusely reflected light is cast in the direction of the solar beam for low sun, they showed also a rapid approach to uniformity of distribution as the sun grows higher and higher. The scarcity of the material does not allow the distribution of light to be determined as precisely as could be wished, and the several points of observation were connected merely with straight lines to avoid implying a knowledge not yet gained. But the several broken lines thus formed seemed better adapted to serve for estimating the cloud albedo, or total diffuse reflection over a hemisphere, than a mere average of observations without regard to distribution would be. Accordingly, the area of the figure included under each of the lines has been measured, and from this has been obtained the average diffuse reflection corresponding to a definite zenith distance of the sun. These data are included in the following table, in columns 1, 2, 3. Columns 4 and 5 will receive further explanation below.

TABLE 26.—*Reflecting power of clouds.*

Sun zenith distance.	Cloud nadir distance.	Cloud reflection, average of zones.	Corresponding reflecting power (uncorrected).	Reflecting power corrected for sky radiation.
75	88	91×10^{-7}	0.86	0.76
70	88	89	.84	.74
65	88	89	.84	.74
50	88½	78	.73	.65
42	86½	74	.70	.61
30	89½	67	.63	.56
67	81	80	.75	.66
50	82	74(?)	.70	.61
42	84	74	.70	.61
Mean.	....	....	....	.66

While these results include a considerable range of solar zenith distance they represent only the zone from 90° to 80° in nadir distance, which is only about one-fifth of the whole hemisphere. But fortunately there are a few isolated observations at greater nadir distances which will be used with these in determining the cloud albedo as stated below.

A perfect matt surface may be defined as one which reflects diffusely the whole of the light incident upon it, and reflects equally in all directions independent of the angle of incidence of the rays. Every area of such a surface equal in solid angle to the area of the sun on August 22, 1906, would reflect 0.0000106 times as much radiation to the observer as he received directly from the sun, for the solid angle of the sun was 106×10^{-7} of a hemisphere on that day. Accordingly, for any zenith distance of the sun, and for any nadir distance of a perfectly matt cloud, the intensity of the diffusely reflected sun radiation at each and every azimuth would be 106×10^{-7}.

The ratio of the observed average reflection to that of the ideal matt surface is given in column 4.

Thus far no mention has been made of the fact that in all these cloud-reflection experiments the radiation diffusely reflected came not alone from the sun, but also from the sky. The observations made to determine the amount of light coming from the sky and the application of these observations to the problem now in hand are given in the next chapter. It will be necessary to state here only the general result that on clear days the average total radiation of the sky received on a horizontal surface upon Mount Wilson was about 5 per cent of the amount received at normal incidence in the direct beam from the sun outside our atmosphere. Unfortunately, the sky-radiation data are not sufficiently numerous to fix the amounts corresponding to all zenith distances of the sun, but for the purposes here in view no serious error will result by employing the above mean value.

It appears to be nearly immaterial, so far as the diffuse reflection of a whole zone of clouds is concerned, whether we regard the radiation as coming to the cloud from a single direction like that of the sun, or as coming from an entire hemisphere like that of the sky, for there is no very great change of the value in column 3 of Table 26, depending on the change of zenith distance of the source of light. In comparing the light coming to a cloud from the sky with that coming from the sun, within the range of solar zenith distances given in Table 26, the light of the sky will be regarded as 5 per cent of the "solar constant." But in consideration of the smallness of the correction to be determined, and the uncertainty regarding some of its factors, a mean value of 60° will be employed for z, so that the ratio of effective sky light to effective sunlight will be taken as 13.5 per cent.

The values given in column 5 of Table 26 are obtained by dividing those in column 4 by 1.135.

There remain a number of values in Table 25 not used in preparing Table 26. In order to add their testimony in making an estimate of the albedo of clouds, it will be necessary to compare them with the total radiation of sun and sky combined, which a perfectly matt cloud would diffusely reflect into any solid angle equal to that of the sun. This amount on a comparable scale with the values in Table 25 would be $1.135 \times 106 \times 10^{-7} = 120 \times 10^{-7}$ for August 22, and $1.135 \times 107 \times 10^{-7} = 121 \times 10^{-7}$ for September 13. Combining these values with those of column 4, gives column 5 of the following table.

TABLE 27.—*Further determinations of reflecting power of clouds.*

Sun zenith distance.	Cloud nadir distance.	Cloud azimuth.	Radiation of cloud / Radiation of sun ×10⁷.	Cloud reflecting power, corrected for sky radiation.
°	°	°		
[1]76	74	7	191	1.59
[1]73	72	38	71	.59
30	70	0	104	.86
30	62	1	92	.76
30	58	4	75	.62
30	54	2	70	.58
30	38	4	62	.52
30	20	9	51	.42
Mean				.74
Mean, omitting first value				.62

[1] August 22. The remaining values are for September 13.

The mean reflecting power at these eight points, differing widely in cloud nadir distance and corresponding to two different zenith distances of the sun, is thus 74 per cent, and omitting the observation near the position of true, or specular reflection, 62 per cent. This value may be compared with the more weighty value, 66 per cent, which was the mean result at all azimuths, and a variety of zenith distances of the sun, as given in Table 26.

From a consideration of the nadir distances of observation it appears most probable that the average albedo of fog clouds is less rather than greater than the mean values just given. We shall assume it to be 65 per cent; or, in other words, that the earth, if completely covered with low-lying clouds, would reflect toward space 65 per cent of the solar radiation. No measurements have been made of the reflecting power of the cirrus, or ice clouds, but it is probably somewhat higher than that of fog clouds when a sufficient thickness of cirrus clouds is present to cut off substantially all of the direct radiation of the sun.

Heretofore, as has been said, writers who have had occasion to employ a value for the albedo of clouds have estimated it at about 75 per cent, assuming that it is nearly comparable with that of white paper or snow. This view is neglectful of the fact that clouds in the opposite quarter of the heavens from the sun, or in quadrature thereto, are much duller in appearance than these white solids would be when held at nearly the same angles of incidence and reflection. And when it is considered in addition that the clouds are penetrated for many feet by the direct rays of the sun, while paper is penetrated only a small fraction of an inch, there appears no reason to discredit the result of observation above given, namely, that the albedo of clouds is only about 65 per cent. This value will be employed in what follows without distinction as to the zenith distance of the sun, for the observational material is not sufficient to warrant such a distinction.

THE CLOUDINESS OF THE EARTH AND CORRESPONDING REFLECTION.

Arrhenius has given,[1] in his discussion of the effect of carbon dioxide on the temperature of the earth, a summary of the results of cloud observations over the earth's surface. From this statement columns 1, 2, 3, 4 of the following Table 28 are taken. Column 5 gives the mean cloudiness, taking into account the comparative areas of land and water. Column 6 gives the average fractional amounts of radiation lost to the different zones of the earth owing to the reflection of clouds, taking the amount which would reach each zone outside the atmosphere as unity. Column 7 gives the proportion of a hemisphere which the different zones occupy when seen in flat projection, as from the sun. Column 8 gives the average fractional amount of radiation lost to the earth by the reflection of the clouds over the different zones, taking the total amount of radiation outside the atmosphere over the whole earth as unity.

TABLE 28.—*Terrestrial cloudiness and reflecting power.*

Latitude.	Percentage cloudiness.		Percentage area continent.	Percentage average cloudiness.	Percentage reflection ($\frac{65}{100}$ column 5).	Projected area.	Percentage reflection ($\frac{65}{100}$ product columns 5 and 7).
	Continent.	Ocean.					
°							
+90–70	....	....	....	60?	39?	0.0055	0.19
70–60	58.1	66.7	72.1	60.5	39.2	.021	.80
60–50	56.3	67.6	55.8	61.3	39.9	.037	1.47
50–40	45.7	63.3	52.9	54.0	35.1	.056	1.95
40–30	36.5	52.5	42.9	45.7	29.7	.076	2.22
30–20	28.5	47.2	38.8	40.0	26.0	.092	2.38
20–10	28.5	47.0	24.2	42.5	27.5	.104	2.88
+10– 0	50.1	56.7	23.3	55.2	36.0	.108	3.86
– 0–10	54.8	59.7	24.2	58.5	37.9	.108	4.10
10–20	47.8	54.0	22.5	52.6	34.2	.104	3.58
20–30	29.6	49.6	23.3	44.9	29.3	.092	2.67
30–40	38.9	51.0	12.5	49.5	32.1	.076	2.47
40–50	62.0	61.1	2.5	61.1	39.7	.056	2.21
50–60	71.0	71.5	0.9	71.5	46.6	.037	1.69
–60–90	....	....	....	70?	46?	.027	1.21
Total......	....	....	....	....	....	....	33.7

From these figures we conclude that about one-third of the radiation which the sun sends toward the earth is reflected by the clouds toward space, and therefore has no effect whatever on life or meteorology.

If the earth were to become at some future time, or has been at some past time, completely clouded over, the loss by the direct reflection of clouds corresponding to such a state of affairs would be about two-thirds of the whole amount of solar radiation. The consequences of such a loss of radiation in diminishing the earth's temperature are discussed in Chapter IV.

[1] S. Arrhenius, London, Edinburgh, and Dublin Philosophical Magazine, series 5, vol. 41, p. 275, 1896.

Chapter III.

INDIRECT SOLAR RADIATION.

Measurements were made on Mount Wilson in 1905 and 1906 to determine the relative amounts of radiation received directly from the sun and indirectly by scattering from the sky. These measurements were neither as numerous nor as accurate as desired, but some of the more trustworthy of them will be given. It is expected to make other and better measurements of this kind in future.

APPARATUS AND METHODS FOR MEASURING DIFFUSE SKY RADIATION.

In 1905 a bolometer was mounted upon a theodolite so as to be pointed directly at the sky or sun, and with known angles of altitude and azimuth. A diaphragm with a measured circular aperture was placed at a measured distance in front of the bolometer, and a sheet of glass was fixed near this diaphragm to screen the bolometer from wind and to prevent the exchange of radiations of long wave-length emitted by the bolometer and the sky, respectively. Every point of the bolometer was the apex of a cone of sky light whose solid angle included the circular aperture of the diaphragm. When observing the sun, each point of the bolometer received a cone of direct sun rays whose base was the sun; and, in addition, the cone of sky rays limited by the circular aperture. The aperture of the diaphragm was so small, and the total energy of the scattered radiation from the sky is so small a fraction of that received directly from the sun, that it has not been thought necessary to correct for this superposition of sky light on sunlight.

The measurements were conducted by two observers, one of whom set and read the theodolite, exposed the bolometer by removing a black shutter, and recorded all observations, while the other read the galvanometer. In order to reduce the effect of direct sunlight to nearly the same magnitude as that of sky light a resistance of 5,000 ohms was inserted in the galvanometer circuit when the bolometer was exposed to the sun. It was, therefore, necessary to determine a factor of reduction to allow for the effect of 5,000 ohms. For this purpose a beam of sunlight was reflected from a cœlostat, and means were provided for regulating its intensity at any desired amount by the use of a slit placed at about 5 meters from the bolometer.

Observations were then made of the comparative deflections when 5,000 and 2,000 ohms, 2,000 and 1,000 ohms, 1,000 and 500 ohms, etc., were inserted in the galvanometer circuit. In this way by a series of steps the effect of 5,000 ohms was at length obtained. The method, to be sure, tacitly assumes that the proportionality of the bolometer indications is independent of the intensity of the light; or, in other words, that the bolometer is heated half as many degrees by sunlight of half intensity as by sunlight of full intensity; and this is probably not strictly the case when radiation as intense as that of the sun is in question.

Another source of error may arise from the fact that the bolometer was inclined at different angles during the observations of different parts of the sky, and on this account may have been unequally sensitive at different times. This seems the more likely from the fact that the electrical balance of the bolometer had to be readjusted slightly for every new altitude of observation. A further difficulty arose from the unsteadiness of the galvanometer zero.

Taking these several things in consideration, the observations of 1905 are not entitled to as great weight as those of 1906.

SKY-RADIATION OBSERVATIONS OF 1905.

TABLE 29.—*Sky-radiation observations of August 18, 1905.*

[Sky exceptionally clear. Angular area of sun 0.00714 that of observed portion of sky.]

Azimuth (from N-E-S-W).			Zenith distance.		Radiation for equal solid angles Sky./Sun.
Sky.	Sun.	Sky-Sun.	Sky.	Sun.	
°	°	°	°	°	
180	123	57	55	34	29×10^{-8}
240	....	117	....	....	79
300	....	177	....	....	64
0	127	−127	....	32	129
60	....	− 67	....	....	0
150	130	20	....	....	164
180	132	48	80	30	164
190	....	58	....	....	121
120	133	− 13	....	....	193
100	135	− 35	....	....	164
180	136	44	20	28	100
240	....	104	....	....	0
300	137	163	....	....	57
0	....	−137	....	....	14
60	138	− 78	....	....	79
120	....	− 18	....	....	464
110	139	− 29	90	26	300
180	150	30	45	23	71
240	151	89	....	....	29
300	153	147	....	....	43
45	155	−110	....	....	14
120	160	− 40	....	....	71
90	160	− 70	....	....	50
180	165	− 15	65	....	171
240	167	73	....	....	107
60	170	−110	....	....	50
120	175	− 55	....	....	86
180	180	0	30	22	243
240	....	60	....	....	71
300	....	120	....	....	29
0	....	180	....	....	0
60	....	−120	....	....	21
120	....	− 60	....	....	100

These observations grouped in zones with reference to the zenith distance of the observed sky have been plotted with differences of azimuth as abscissæ and observed ratios of brightness as ordinates. In this way the intensity of the direct beam of the sun has been compared with the average intensity of sky radiation coming from each of several zones of differing zenith distance. These data are given in the following table:

TABLE 30.—*Average intensity of sky radiation August 18, 1905.*

Zenith distance.		Average ratio of intensity of radiation $\frac{\text{Sky}}{\text{Sun}}$.
Sun.	Sky.	
°	°	
27	20	[1] 78×10^{-8}
22	30	[1] 82
23	45	67
32	55	81
23	65	93
29	80	116

[1] In deriving this value the extremely bright region near the sun is neglected. An allowance for the brightness of the immediate neighborhood of the sun will be made separately.

So long as only one small region of the sky is in question, its radiation may well be considered as coming normally upon a receiving surface, but the radiation of the entire vault of the sky can not all be received upon a plane surface at normal incidence. In what follows a summation of the radiation of the sky will be given with the condition that it is to be considered as received upon a horizontal flat surface. Allowance is therefore to be made not only for the area of the several zones of the sky, but also for the inclination at which their rays would meet the surface mentioned. From the results given in Table 30 other values for intermediate zones have been obtained by interpolation. To allow for the bright region near the sun it has been assumed for convenience sake that this region is the zone lying within 15° of the zenith, but the effect of it is diminished by multiplying by the cosine of the sun's zenith distance. From these remarks the following table will be understood:

TABLE 31.—*Average brightness of the sky August 18, 1905.*

I. Zenith distance of zone....	0°–15° (assumed sun region).	15°–35°	35°–50°	50°–60°	60°–70°	70°–80°	80°–90°	Sums.
II. Area of zone................	0.034.........	0.147	0.176	0.143	0.158	0.168	0.174	1.000
III. Cosine of zenith distance...	[1] (0.91).......	.91	.73	.57	.42	.259	.087	....
IV. Mean ratio radiation $\frac{\text{Sky}}{\text{Sun}}$..	[1] 500 ($\times10^{-8}$)	79	70	81	93	107	127	....
V. Product lines II and IV...	17.5 ($\times10^{-8}$)	11.6	12.3	11.6	14.7	18.0	22.1	117
VI. Product lines II, III, and IV.	15.9 ($\times10^{-8}$)	10.6	9.0	6.6	6.2	4.7	1.9	55

[1] See remark made above, and also observation at 20° zenith distance 18° east of sun, included in Table 29.

From these figures it is shown that on August 18, 1905, with the sun at about 25° zenith distance, patches of sky equal in angular area to the sun, gave on the average 117×10^{-8} times the amount of radiation in the direct beam of the sun, if received at vertical incidence. If received on a horizontal surface the corresponding value is 55×10^{-8}.

On August 18, 1905, the sun occupied 106×10^{-7} times the angular area of the entire sky, so that in accordance with results just given, the total sky radiation upon a horizontal surface would be 5.2 per cent of the amount of direct solar radiation which would be received upon a surface of equal area placed at right angles to the solar beam. If received on a spherical surface the diffused radiation of the sky would be 11 per cent of the direct radiation of the sun.

From pyrheliometer measurements, combined with estimates of the "solar constant," it was found that the intensity of direct solar radiation at the earth's surface at this time was 80 per cent of the amount outside the earth's atmosphere. Accordingly the radiation of the entire sky upon a horizontal area on Mount Wilson was 4.2 per cent of the solar radiation which would have fallen upon the same area if placed at right angles to the beam outside the earth's atmosphere. For a spherical surface the proportion is 8.8 per cent.

SKY-RADIATION OBSERVATIONS OF 1906.

Omitting other less satisfactory observations of 1905, we next take up the sky-radiation measurements of 1906. These were made with the apparatus on the tower described in the account of cloud-reflection work. (See Chapter II, Part II.) Without including isolated observations made at points near the horizon on several days when clouds were being observed, the sky-radiation measurements which will be given were made on September 8, 1906, and October 19, 1906, respectively. On the former occasion both of the plane mirrors shown in Plate XIX were employed as in cloud observations, but on October 19 only the lower one was in use. The results are given briefly in the following table. In the last column the results appear as corrected for the differential selective effect of the mirrors on sunlight and sky light. This correction will be explained on a later page.

TABLE 32.—*Sky-radiation observations of 1906.*

SEPTEMBER 8, 1906.

Azimuth (N-E-S-W).			Zenith distance.		Observed radiation for equal solid angles $\frac{Sky}{Sun}$.	Radiation ratio corrected for mirrors.
Sky.	Sun.	Sky-Sun.	Sky.	Sun.		
°	°	°	°	°		
117.8	248.0	−130.2	66.3	52.0	81×10^{-8}	112×10^{-8}
122.1	249.0	−126.9	85.4	53.0	219	301
92.4	249.7	−157.3	62.8	53.5	77	106
247.8	251.0	− 3.2	60.9	55.0	408	566
227.1	252.0	− 24.9	85.5	56.0	586	809
158.6	252.5	− 93.9	65.2	56.5	97	134
110.1	252.7	−142.6	67.3	56.8	99	137
OCTOBER 19, 1906.						
91.6	135.1	− 43.5	79.2	55.8	220	295
94.8	136.0	− 41.2	67.4	55.5	164	219
103.1	138.6	− 35.5	54.5	54.0	123	165
118.2	139.5	− 21.3	44.6	53.6	141	190
139.5	146.2	− 6.7	40.5	50.4	212	285
160.7	147.8	+ 12.9	31.1	49.8	261	350
1.0	149.6	−149.6	49.7	49.2	73	98
36.9	150.2	−113.3	50.4	48.9	81	108
91.6	155.0	− 63.4	79.2	47.4	166	222
71.5	156.0	− 84.5	77.9	47.0	127	171
78.4	158.0	− 79.6	29.2	46.5	73	98
304.2	159.4	+144.8	27.8	46.2	51	68

The corrected measurements just given were plotted with reference to the difference of azimuth between sun and sky, and the average ratio of radiation of sky and sun was then obtained after the manner already described. From this process the following values are derived:

TABLE 33.—*Average intensity of sky radiation, 1906.*

Zenith distance of—		Average ratio intensity of radiation. $\frac{Sky}{Sun}$.
Sun.	Sky.	
°	°	
47.3	29.4	[1] 122×10^{-8}
51.2	47.9	[1] 129
54.7	64.5	[2] 185
50.0	78.8	[1] 214
54.5	85.5	[2] 500 (?)

[1] Observations of October 19.
[2] Observations of September 8.

We proceed as with the observations of 1905, excepting that as measurements were made near the sun and at well-determined places no special treatment of this region is necessary.

Thus we obtain:

TABLE 34.—*Average brightness of the sky, 1906.*

I. Zenith distance of zone	0°–15°	15°–35°	35°–50°	50°–60°	60°–70°	70°–80°	80°–90°	Sum.
II. Area of zone	0.034	0.147	0.176	0.143	0.158	0.168	0.174	1.000
III. Cosine zenith distance	.98	.91	.73	.57	.42	.259	.087	. . . .
IV. Mean ratio radiation $\frac{\text{Sky}}{\text{Sun}}$ . . .	115 ($\times 10^{-8}$)	122	128	150	185	210	460	. . . .
V. Product lines II and IV	3.9 ($\times 10^{-8}$)	17.9	22.5	21.4	29.2	35.3	80.0	210
VI. Product lines II, III, and IV	3.8 ($\times 10^{-8}$)	16.3	16.4	12.2	12.3	9.1	7.0	77

The mean angular area of the sun at the times corresponding to these observations was 104×10^{-7} hemisphere. Accordingly, from the observations of September 8 and October 19, 1906, the total diffused solar radiation from the sky, if received in each instance on a spherical surface, is found to be $\frac{210\times10^{-8}}{104\times10^{-7}}=20$ per cent of the radiation received directly from the sun at 51°.5 zenith distance.

When the sky light is assumed to fall on a horizontal surface, but still comparing it with sunlight received directly at normal incidence, the proportion is $\frac{77\times10^{-8}}{104\times10^{-7}}=7.4$ per cent.

To compare with the intensity of solar radiation outside the atmosphere the intensity of the direct sunbeam at 51°.5 zenith distance may be regarded as about 75 per cent as great as that outside the atmosphere. Hence, from the observations of September 8 and October 19, 1906, the total diffuse sky radiation if received at normal incidence would be 15 per cent, and if received on a horizontal surface 5.6 per cent of the intensity of the direct beam received at normal incidence outside the atmosphere.

Compared with the results found for August 18, 1905, the values just given are a little larger, but are on the whole quite as close as the changeableness of the brightness of the sky, the great difference in apparatus and methods of measurement, and the small number of observations made would lead us to expect. For convenient reference the several results are set down in the following table:

TABLE 35.—*Diffuse reflection of the sky on Mount Wilson.*

Date observed.	Sun's zenith distance (average).	Ratio of intensity of radiation of sky and sun.					
		Average sky and direct sun—Equal angular areas.		Total sky and direct sun—Latter at normal incidence.			
				Sun at earths' surface.		Sun outside atmosphere.	
		Normal incidence.	Sky light on horizontal surface.	Sky normal incidence.	Sky on horizontal surface.	Sky normal incidence.	Sky on horizontal surface.
	°			*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
August 18, 1905	27.8	117×10^{-8}	55×10^{-8}	11	5.2	8.8	4.2
September 8, 1906 } October 19, 1906 }	51.5	210×10^{-8}	77×10^{-8}	20	7.7	15.0	5.6

CORRECTION OF REFLECTING POWER OF CLOUDS FOR SKY RADIATION.

Taking the values in the last column as a basis, and (for lack of sufficient data, making no allowance for different zenith distances of the sun), we may say that on the average the horizontal cloud layer whose reflecting power was observed, as stated in Chapter II, Part II, received (0.05)(2.0)=0.1 calorie per square centimeter per minute of diffusely reflected radiation. Speaking roughly, the direct solar radiation on each square centimeter was (0.75)(2.0) cosine Z=(1.5 cosine Z) calories per minute. In the observations of August 22, 1906, cosine Z varied from 0.22 to 0.76, and in those of September 13, 1906, cosine Z was 0.86. Not having determined the change, if any, of the total amount of diffused sky light received on a level surface depending on the zenith distance of the sun, it will not be worth while to take account individually of the different solar zenith distances, and hence an average value of the correction for sky radiation will be employed, and taking all things in consideration this may well be $\frac{0.1}{1.5 \text{ cosine } 60^\circ}=13\frac{1}{2}$ per cent. Accordingly, as stated in the description of the cloud experiments, the total light which fell upon the clouds was estimated at 1.135 times the intensity of the direct beam of the sun.

THE QUALITY OF DIFFUSED SKY LIGHT.

In connection with the measurements of the total intensity of the radiation diffusely reflected by the sky over Mount Wilson, a few observations were made to determine the distribution of intensity in the spectrum of diffused sky radiation. For this purpose the sunlight was reflected into a darkened room by a two-mirror cœlostat, and, after passing through a small aperture, traveled about 5 meters till it reached a short focus double-convex lens of glass, by which the rays were made very divergent, after passing through the focus. At a little distance from the lens was a fine-ground-glass screen of microscope cover glass, and after passing through this the light fell upon the lower half of the slit of a spectroscope. The distance from the lens to the ground glass could be altered by sliding the lens on a scale.

Another beam of light was reflected by a 15-inch plane mirror mounted as an alt-azimuth, and this beam, passing parallel to and above the sunbeam, entered the darkened chamber and was reflected downward by a plane mirror. It then traversed a ground-glass plate like the one in the sunbeam, and was reflected into the upper half of the spectroscope slit by means of a totally reflecting prism.[1] There was thus superposed at the eyepiece of the instrument the spectrum of the sky and the spectrum of the direct sunbeam, and means were at hand to adjust the intensity of the latter to equal the intensity of the former, according to eye observations.

Preliminary trials were made at three different points in the spectrum, and by two observers, to see if the measured movement of the lens upon the scale was able to yield correct estimates of the comparative intensity of the two spectra. For this purpose a rotating disk whose aperture was 0.187 times that of a complete circle was introduced in one of the beams of light, and a match of intensities in the two spectra was obtained at three different settings of the spectroscope both with and without the rotating disk. These measurements were reduced by taking into account the distances from the lens to the ground glass and from the lens to the small aperture, and the focal length of the lens. From these measurements the aperture of the rotating disk was computed with the following results. Each observer made two determinations on each color, and the table gives the mean of these.

Color of light.	Red.	Green.	Blue.
Observer.	Computed aperture of rotating disk.		
C. G. A.	0.181	0.175	0.200
L. R. I.	0.176	0.187	0.169
Mean.	0.1785	0.181	0.1845

General mean, 0.181. Real value, 0.187.

The general tendency appears to be toward too low values; and this was thought to be due to the distribution of the stray light of the room at the time of the observation. Attention was paid to correcting this source of error in later experiments. Though the measurements indicate that settings could not be made with great accuracy, yet considering the variability of the color of the sky and other difficulties, these rough means of observation seemed to yield results as good as were required to gain a general idea of the quality of sky light.

[1] There being two mirrors, a lens, and a ground glass in the solar beam, and two mirrors, a prism, and ground glass in the sky beam, no correction was required for absorption. The sunlight was mixed from all parts of the sun's disk.

Observations of the quality of diffused sky light were made on Mount Wilson on October 17, 1906. Mr. J. Evershed, then visiting the Solar Observatory on his way to India, and Mr. Olmsted, of the staff of the Solar Observatory, made many of the observations, and aided greatly in arranging the apparatus. Omitting the details of observation and reduction, the results are given in the following table. In stating them the sky light and sunlight are assumed to be approximately in the ratio of 100 to 1 at a wave-length of 0.66 μ.

TABLE 36.—*Ratio of intensities in spectra of sky and direct solar beam.*

Observer.	Hour angle sun.	Zenith distance.		Azimuth, sun-sky.	Wave-length.					
		Sun.	Sky.		μ 0.422.	μ 0.457.	μ 0.491.	μ 0.556.	μ 0.614.	μ 0.660.
	h. m.	°	°	°						
J. E.	0 27 E.	43	23	79	655	521	294	188	106	100
J. E.	0 14 W.	43	41	12½	800	407	273	172	104	117
J. E.	1 41.	49½	73	92	596	403	297	164	140	111
C. G. A.	2 11.	53	72½	152	546	381	229	....	108	....
C. M. O.	2 28.	55½	72½	156	683	412	338	175	129	88
J. E.	2 46.	58	17	146	574	425	317	191	124	104
General mean.					642	425	309	187	121	105
Mean near horizon.					608	399	323	189	135	102
Mean near zenith.					676	451	295	184	111	107

Although obviously the probable error of the observations is rather large, the mean result seems to be accurate enough to represent pretty closely the comparative distribution of light in the spectra of diffused sky light and direct sunlight as observed on Mount Wilson, and there is even some indication (as there should be) of a bluer quality in the sky light nearer the zenith. In order to represent the real distribution of diffused sky light in the normal spectrum, the mean values just obtained may be multiplied by the intensities of sunlight in the normal spectrum as it would be observed on Mount Wilson at a solar zenith distance of about 50°. This procedure yields results given in the following table. The units of intensities are wholly arbitrary.

Wave-length.	μ 0. 422	μ 0. 457	μ 0. 491	μ 0. 556	μ 0. 614	μ 0. 660
Intensity of direct sunlight—zenith distance, 50°.	186	232	227	211	191	166
Intensity of sky light.	1, 194	986	701	395	231	174
Ratio.	642	425	309	187	121	105

The Hon. J. W. Strutt (Lord Rayleigh), in his article on the blue of the sky,[1] gives the following values derived from theory and observation, respectively, of the ratios of intensity in the neighborhood of some of the Fraunhofer lines in the spectra of diffused sky light and sunlight. For comparison there are given also values found by interpolation representing the mean results obtained on Mount Wilson.

Fraunhofer line	C	D	b_3	F
Ratio computed by Rayleigh	25	40	63	80
Ratio observed by Rayleigh	25	41	71	90
Ratio observed on Mount Wilson	25	35	60	77

THE REFLECTION OF SUNLIGHT AND SKY LIGHT BY SILVERED MIRRORS.

The results given above on the comparative quality of sky light and direct sunlight have been used in the following manner to determine the correction for the different effect of silvered mirrors on sunlight and sky light, as required in the reduction of observations of different sky-radiation measurements of September 8 and October 19, 1906. The following table illustrates in abbreviated form the method of determining the comparative losses of sky light and sunlight when both are reflected successively by three silvered mirrors. Account was made in the complete computations of the water-vapor bands of the infra-red spectrum, but this did not much influence the result. The data of lines II and IV are taken from bolographic work, and represent the sun at about 50° from zenith and the silvered surfaces about one month old.

Reflection of sunlight and sky light by silvered mirrors.

I. Wave-length	μ 0.385	μ 0.395	μ 0.405	μ 0.430	μ 0.459	μ 0.498	μ 0.553	μ 0.636	μ 0.775	μ 1.035	μ 1.533	μ 2.082
II. Intensity of prismatic solar spectrum from a bolograph of Oct. 18, 1906	68	179	239	289	448	551	727	929	1,245	1,243	742	185
III. Ratio sky to sun	8.39(?)	7.65(?)	7.00	5.71	4.40	3.08	1.89	1.07	.80(?)	.75(?)	.75(?)	.75(?)
IV. Reflection 3 mirrors (old silver)	.304	.311	.322	.344	.373	.422	.495	.595	.725	.833	.870	.870
V. Product II, III	570	1,367	1,673	1,650	1,971	1,697	1,374	994	996	932	557	139
VI. Product II, IV	21	56	77	99	167	233	360	553	902	1,037	645	161
VII. Product II, III, IV	176	428	539	565	735	718	680	592	772	780	484	121

Σ II=6,837 Σ V=13,920 Σ VI=4,311 Σ VII=6,590

$$\text{Correction}=\frac{\Sigma\text{ V}\times\Sigma\text{VI}}{\Sigma\text{ II}\times\Sigma\text{ VII}}=1.33$$

In correcting the sky-radiation observations of October 19, 1906, the coefficient 1.34 was employed, and in correcting those of September 8, 1906, 1.38. The latter value was computed from a bolograph of September 8, and assuming reflections from four mirrors instead of three. In all this work the ray cone described in

[1] London, Edinburgh, and Dublin Philosophical Magazine, series 4, vol. 41, p. 114, 1871.

Chapter II of Part II was treated as equal to one reflecting surface, though in reality it transmitted some light without reflection, some with one, and some with two or more reflections.

The radiation reflected by clouds was regarded as of the same quality as direct sunlight, and no correction for the effect of silvered surfaces was deemed necessary, therefore, in the determination of the reflecting power of clouds.

A MINIMUM VALUE OF THE "SOLAR CONSTANT."

Langley pointed out in his chapter on Sky Radiation in the Report of the Mount Whitney Expedition that the solar radiation outside the atmosphere must certainly exceed in its intensity the direct solar beam at the earth's surface by a greater amount than is supplied by indirect radiation of the unclouded sky; and to the latter may be added also the amount absorbed by the oxygen and water vapor of the atmosphere. The matter appears in its clearest form if we imagine the sun (at mean solar distance) to be in the zenith, and consider the earth's surface as a vast plain covered by a thin layer of air. Then if we could ascend to the upper limit of the atmosphere the amount of solar energy on each square centimeter would be the "solar constant." At a point on the earth's surface the amount received on each square centimeter from the direct solar beam would be less than that outside the atmosphere, first, because of the diffuse reflection of rays, and second, because of the actual absorption of rays in the atmosphere. A very simple computation shows that the sum of all the rays diffusely reflected within the atmosphere from the direct vertical beam of one centimeter cross section coming from each point on the sun, and reaching the earth's surface finally at near or distant points, either by one or many reflections, is exactly equal to the sum of all the rays reaching each square centimeter of the earth's surface and coming from all parts of the sky. But some of the rays diffusely reflected never reach the earth's surface at all, and hence the total sky light reaching each square centimeter of the earth's surface is less than the loss by diffuse reflection from the solar beam of one square centimeter cross section.

If to the pyrheliometer reading corresponding to zenith sun we add the diffusely reflected sky light which falls on a square centimeter of the earth's surface, and to this the amount of radiation which appears to have been absorbed from the direct solar beam by the absorption of water vapor, as evidenced in the infra-red bands of the solar spectrum, the result must be less than the "solar constant," by an amount which will indicate approximately the sum of the nonselective absorption of the atmosphere and the diffuse reflection of the atmosphere to space.

Thus from Mount Wilson data of October 18, 1906, the pyrheliometer reading at air mass 1.39 was 1.625 calories, and (by a short extrapolation) at air mass 1.00 would have been 1.680 calories. The area of the bolographic curve at air mass

1.39 was 13.7 times the area of the gaps left in it by the selective absorption of water vapor and oxygen, so that the loss by selective absorption was at least 0.119 calorie. On October 19, 1906, the radiation reflected by the sky on a horizontal surface was 7.7 per cent of that received normally in the direct beam of the sun at 51°.5 zenith distance. Assuming the same value for October 18 when the direct beam at this zenith distance gave 1.591 calories, the sky radiation was then 0.122 calorie. Adding the three quantities the result is 1.921 calories. The intensity of solar radiation outside the atmosphere on October 18 was found to be 1.96 calories uncorrected for solar distance, and the difference, 0.04 calorie, may be supposed to represent the sum of the nonselective absorption of the atmosphere above Mount Wilson and its reflection to space. This is about one-third the assumed value of the sky radiation diffused toward the earth, but in a quantity determined as a small difference of two much larger quantities, themselves liable to error, not much faith is justified in the accuracy of the former. If, for instance, the estimate of the "solar constant" should be 1 per cent too small, this would materially alter the ratio just found.

From the computation just made, and after allowing for solar distance, we may conclude that on October 18 the "solar constant" was probably in excess of 1.89 calories.

Chapter IV.

INCOME AND OUTGO OF HEAT FROM THE EARTH, AND THE DEPENDENCE OF ITS TEMPERATURE THEREON.

HEAT AVAILABLE TO WARM THE EARTH.

Stellar radiation, chemical sources of heat, radioactive substances, internal heat of the earth, and heat of shrinkage will all be neglected as of trifling consequence compared with the heating of the sun, in estimating the present income of heat to warm the earth. The sequel will show that the known heating of the sun and the known temperature of the earth accord well with known laws of radiation, thus justifying the neglect of other sources of heat, apparently negligible a priori.

Concerning solar radiation, there is a question what proportion should be regarded as actually available to warm the surface of the earth, because the influence of radiation absorbed in the higher parts of the atmosphere will be little felt at sea-level. Two estimates have been prepared, one giving the proportion of solar radiation absorbed anywhere below the outer limits of our atmosphere, and the other including all that is absorbed below the level of Mount Wilson.

As there are numerous considerations involved in the preparation of these estimates, it will be of advantage to state briefly in advance the steps which are to be taken.

The radiation absorbed by the earth and its atmosphere is equal to the total amount of radiation sent toward the earth by the sun, minus the total amount of this which is reflected away. We propose first to determine the proportion reflected away, and afterwards to discuss the amount remaining, which is absorbed, and to decide how much of it is absorbed below the Mount Wilson level.

In order to determine the total amount reflected away, we have to take account of the reflecting power of the clouds and of the unclouded air, and the reflecting power of the earth's surface. Besides this we must consider the decrease in the amount of radiation available to be reflected, as we pass successively from the higher atmosphere and its clouds to the lower atmosphere and its clouds, and finally to the earth's surface. This decrease is due in part to the selective absorption of the gases of the atmosphere, in part to the diffuse reflection toward space of the atmosphere itself. Allowance must be made for the fact that the air interposes a hindrance to the outgo of reflected rays, as well as to the incoming rays. Finally, we must consider not alone the direct incoming solar rays, but also those coming indirectly from the sky.

Before proceeding to the final conclusions, certain preliminary estimates are required; and first in order to determine the radiation reflected to space, there must be considered the total amounts of radiation which reach, respectively, (1) the clouds as a whole, (2) that portion of the clouds lower than the Mount Wilson level, and (3) the earth's surface. In each instance we shall consider the unclouded intervals of time alone as available to furnish radiation for reflection to space; for in the experiments by which the reflecting power of clouds was determined, there was included in the amount of radiation regarded as reflected by the clouds all that portion, if any, which had passed through the clouds and been reflected and was on its way out again to space. In other words, the small intensity of the radiation which, after passing through the clouds twice, is on its way to space, is chiefly taken account of in the coefficient of cloud reflection employed here, and it is, besides, too small to be of importance.

RADIATION AVAILABLE TO BE REFLECTED BY CLOUDS AND BY THE EARTH'S SURFACE.

The radiation which reaches the clouds as a whole comprises the direct beam of the sun and the radiation diffused by the sky. At the level of Mount Wilson the former, as stated in Chapter I, Part II, was found to be in clear weather about 75 per cent of the total radiation which the sun sends the earth. The reflected sky radiation at the same level, as stated in Chapter III, was found to be in clear weather 5 per cent of the intensity of the solar radiation outside the atmosphere, regarding the sky light as received on a horizontal surface. We must, however, consider the relative areas involved. In the summation of the total radiation the sun sends the earth the area involved is πR^2, if R represents the earth's radius; but the total area to be summed up for the sky reflection is somewhat greater than $2\pi R^2$. The twilight portion of this area receives light of much less than average intensity, and probably this twilight will be about sufficient to make up for the regions where the sun is so low that the intensity of sky light falls decidedly below its average amount.

We conclude, therefore, that in clear weather 10 per cent of the solar radiation coming toward the earth reaches the level of Mount Wilson by diffuse reflection and 75 per cent directly. Accordingly 85 per cent of the solar radiation would reach this level if there were no higher clouds.

At the higher levels the sky radiation will be of course diminished, but the direct radiation will increase by more than the sky radiation diminishes, and, besides, there is an increase, owing to the decrease of selective absorption of water vapor and oxygen, so that a considerably larger fraction of the sun's radiation than 85 per cent must reach the level of the highest clouds. Let us then assume, for want of more accurate knowledge, that the average amount of radiation which reaches the higher clouds during the interval when they are present is 90 per cent of the total radiation the sun sends the earth.

At the surface of the earth, if Washington be regarded as a sample, the amount of direct sunlight in clear weather for the whole world is stated in Chapter I of Part II to be 50 per cent of the amount the sun sends toward the earth. Of the 50 per cent which does not reach the earth's surface, 12 per cent is stated in the same chapter to be absorbed by oxygen and water vapor, so that 38 per cent represents the sum of the radiation nonselectively absorbed by the air, that reflected diffusely toward space by the sky, and that which is reflected diffusely to the earth's surface by the sky. For lack of more definite information, it will be assumed here that of this 38 per cent one-half reaches the earth's surface by reflection, one-fourth is reflected by the atmosphere to space, and one-fourth absorbed nonselectively.

In accordance with these estimates we regard the amount of radiation available to be reflected by the earth's surface in clear weather to comprise 69 per cent of the amount the sun sends toward the earth. Of this total percentage 50 per cent is furnished by the direct beam and 19 per cent by diffuse reflection from the sky.

THE REFLECTING POWER OF THE EARTH'S SURFACE.

The reflecting power of the earth's surface as a whole is uncertain, but the following data, which have been gathered from several sources by Mr. H. H. Kimball,[1] will serve to make an estimate.

According to Zöllner, the albedo of the moon is 0.1735. At 20° incidence the reflection of various substances is given by him as follows: Fresh snow, 0.783; white paper, 0.700; white sandstone, 0.237; clay marl, 0.156; moist earth, 0.079; water, 0.021. According to Tyndall, the reflecting power of water at various angles of incidence is as follows:

Angle of incidence	0°	40°	60°	80°	89°.5
Reflection	0.018	0.022	0.065	0.333	0.721

In view of the facts that three-fourths of the globe is covered by water, that this water is often rough, and that its reflecting power varies greatly with the angle, there is much uncertainty in assigning a value of reflecting power of the earth as a whole. But recalling that a considerable part of the sky light is near the horizon, that one-fourth of the area of the earth as seen from the sun receives light at a greater angle of incidence than 60°, and particularly taking note of the roughness and foamy condition of a considerable portion of the water, it seems reasonable to assign a mean reflecting power of 6 per cent for the watery part of

[1] Monthly Weather Review, 1901, page 209.

the earth. For the remainder, taking into account the considerable snowy regions and deserts, it seems fair to assign 15 per cent as a mean value, so that the average reflecting power of the earth's surface may be taken as 8 per cent. This estimated value seems more likely to exceed the true one than to fall below it.

REFLECTION OF THE AIR.

In accordance with preceding statements, there is received in clear days at the Mount Wilson level from sun and sky 85 per cent of the radiation which reaches the outer limit of the atmosphere. According to the data given in Chapter I of Part II, 9 per cent is absorbed by oxygen and water vapor, so that 6 per cent represents the reflection to space and the nonselective absorption combined. Assuming that for the air above Mount Wilson these quantities are in the proportion of two to one, then there is a reflection to space by the atmosphere above Mount Wilson amounting to 4 per cent of the total radiation the sun sends the earth. At the mean level of the higher clouds we shall assume 3 per cent for this quantity.

When the low levels of the atmosphere are in question their reflection is much larger, owing to the load of dust they carry; but as heretofore remarked, there is little data for the estimation of the amount of the reflection to space or to the earth. If Washington clear weather is regarded as a fair sample, the sum of atmospheric reflection to space, nonselective absorption and reflection to the earth in clear weather amounts altogether, as has been stated above, to 38 per cent of the solar radiation which is sent toward the earth. Dividing this quantity in the ratio already proposed, namely, one-half scattered in the direction of the earth's surface and the remaining half equally divided between reflection to space and nonselective absorption, we find about 9 per cent reflected to space.

THE TOTAL REFLECTION TO SPACE OR ALBEDO OF THE EARTH.

According to what has been said in Chapter I of Part II, the surface of the earth receives radiation during the absence of clouds 48 per cent of the time. During this interval, as stated above, it receives in the direct beam 50 per cent and from the sky 19 per cent of the radiation sent toward the earth by the sun. Accordingly, 0.48 (50+19) or 33 per cent of the solar rays is reflected at the earth's surface. The reflecting power there being 8 per cent, there will be reflected 2.6 per cent of the whole, and of this about a tenth will be absorbed by the atmosphere, so that 2.3 per cent will eventually be reflected to space from the surface of the earth.[1]

Below the level of Mount Wilson 0.4 of the cloudiness is assumed to be found, as has been stated in Chapter I of Part II, so that as the total cloudiness of the

[1] This is so small a proportion of the albedo of the earth that probably an observer on the moon would hardly be able to distinguish the features of the earth's surface near sea-level, because he would be blinded to them by the much greater amount of light reflected by the atmosphere and clouds.

earth is 52 per cent, the cloudiness of the lower layers is $0.4\times 52=21$ per cent.[1] According to the data given in Part II, Chapter II, the reflecting power of these clouds is 65 per cent, and the radiation reaching them is, as we have stated in the present chapter, 85 per cent of the average intensity outside the atmosphere, so that they add 11.6 per cent to the radiation reflected. Assuming that about one-twentieth of this contribution is absorbed by the atmosphere, there remains 11 per cent reflected by the low clouds to space.

The clouds above the Mount Wilson level represent, in accordance with what we have said, 0.6 of the whole cloudiness, or 31 per cent, and the radiation reaching them is 90 per cent of the average intensity outside the atmosphere. Assuming for them a reflecting power of 65 per cent, their total reflection will be 18.1 per cent. Allowing about one-fiftieth for absorption, there remains 17.7 per cent.

The reflection of the air is summed up as follows, in accordance with the values given in this chapter: During cloudless weather, $48\times 0.09=4.3$ per cent; during the presence of low clouds, $21\times 0.04=0.8$ per cent; and during the presence of high clouds, $31\times 0.03=0.9$ per cent, making up altogether 6 per cent as the reflection of the atmosphere to space.

Finally, then, the earth's surface reflects 2.3 per cent, the low clouds 11 per cent, the high clouds 17.7 per cent, the atmosphere unclouded 6 per cent, making a grand total of 37 per cent for the aldebo of the earth.[1]

The remaining 63 per cent of the solar radiation is absorbed by the earth, the clouds, and the air. If the mean value of the "solar constant" is 2.1 calories and the radius of the earth is denoted by R, this amount is $1.32\pi R^2$ calories per minute.

AMOUNT OF HEAT ABSORBED BELOW THE MOUNT WILSON LEVEL.

We may determine the amount of heat absorbed below the Mount Wilson level by adding together all the quantities which are not absorbed below this level and subtracting their sum from the total amount of radiation sent toward the earth by the sun.

As just estimated, the earth's surface reflects to space 2.3 per cent of the radiation sent toward the earth by the sun, the low clouds 11 per cent, the low atmosphere 4.3 per cent, the atmosphere during the presence of low clouds 0.8 per cent, making a total reflection of 18.4 per cent to be taken into account in this computation. The high clouds cut off 31.2 per cent. The absorption of oxygen and water vapor above the Mount Wilson level during cloudless weather is 9 per cent, and as high clouds are absent 68.9 per cent of the time the allowance for absorption of this kind is 6.2 per cent. About 0.7 per cent may be regarded as reflected by

[1] The reader will note that the uncertainty as to the proportion of the clouds which are low makes little difference in the final result and that the most doubtful part of it is that depending on the reflection of the air to space.

the earth and lower atmosphere and absorbed below the level of Mount Wilson in its course upward, and is therefore to be subtracted from the total reflection.

Altogether, therefore, the amount lost to the surface of the earth and the atmosphere and clouds below the Mount Wilson level is 18.4+31.2+6.2−0.7, or 55.1 per cent. The remaining 44.9 per cent, which may be regarded as efficient to warm the solid and liquid surface of the earth and the air close to the surface, amounts to $0.94\ \pi\ R^2$ calories per minute.

AMOUNT OF HEAT ABSORBED IN THE HIGHER ATMOSPHERE.

Above the Mount Wilson level there is absorbed, according to the two preceding sections, 63−44.9=18.1 per cent of the radiation sent toward the earth, or $0.38\pi\ R^2$ calories per minute. Of this about 9.7 per cent, or about half, is absorbed in the clouds, and some of it may be carried down to the earth by precipitation. The whole is of course available to produce circulation of the atmosphere, and may by this and other means tend somewhat to warm the earth's surface. But it is believed that quite sufficient allowance for all this indirect supply of heat is made by admitting that all the radiation absorbed below the Mount Wilson level is effective to warm the earth's surface.

OUTGO OF HEAT FROM THE EARTH, AND THE EARTH'S TEMPERATURE.

According to what has preceded, we conclude that the average rate of supply of heat at the earth's solid and liquid surface, or what is practically the same, the average rate of loss of heat by the earth's solid and liquid surface is $\left(\frac{0.94\pi R^2}{4\pi R^2}\right)=$ 0.235 calorie per square centimeter per minute, but the rate of radiation of the earth as a planet to space is $\left(\frac{1.32\pi R^2}{4\pi R^2}\right)=0.33$ calorie per square centimeter per minute.

There is to be next considered the connection between the amount of radiation emitted by the earth, and the maintenance of the terrestrial temperature. In order to proceed conveniently, a brief statement is desirable of the laws which govern radiation and temperature.

LAWS OF RADIATION EXCITED BY TEMPERATURE ALONE.[1]

A perfect radiator (or "absolutely black body") emits radiation in proportion to the fourth power of its absolute temperature (Stefan's law). All natural bodies depart more or less from the character of a perfect radiator, and always in the sense that the intensity of their radiation is less at any given temperature than that of a perfect radiator. These departures may involve a deficiency of

[1] In what follows only radiation excited by temperature will be treated unless otherwise expressly stated in the context.

radiation for all wave-lengths, but are generally selective, in that some wave-lengths are less well represented than others as compared with the energy spectrum of a perfect radiator. As the temperature of bodies increases, their radiating power appears to approach closer and closer to that of the perfect radiator. The increase of temperature produces an increase in radiation of all wave-lengths, but the increase is more rapid for the shorter wave-lengths; so that, for instance, while the energy spectrum of the earth is insignificant for wave-lengths less than 2μ, fully 99 per cent of the radiation of the sun is of less wave-length than 2μ.

It will be convenient to express mathematically the laws of radiation of the perfect radiator. For this purpose let the intensity of total radiation be E; the intensity of any given wave-length be J; the maximum intensity found in a spectrum on the normal or wave-length scale of dispersion be J_m; the wave-length be λ; and the absolute temperature be T. Let σ, c_1, c_2, d_1, and d_2 be constants, and e the Napierian base.

Then

$$E = \sigma T^4 \text{ (Stefan-Boltzmann)}$$

$$\left.\begin{array}{r} \lambda_m T = d_1 \\ J_m T^{-5} = d_2 \end{array}\right\} \text{(Wien)}$$

$$J = c_1 \lambda^{-5} \left(e^{\frac{c_2}{\lambda T}} - 1 \right)^{-1} \text{ (Planck)}$$

The following values of the various constants have been determined. If we express E in calories per square centimeters per minute:

$$\sigma = 76.8 \times 10^{-12} \text{ (Kurlbaum).}$$

If we express wave-lengths in microns (μ):

$$d_1 = 2921 \text{ (Paschen)}$$
$$\text{or } 2940 \text{ (Lummer).}$$

The constants d_2 and c_1 are not to be stated so generally as the others, for the reason that the absolute intensity of energy of a single wave-length is not adapted to measurement. But if we call the intensity J_m equal to 1,000 when T=1,000, then

$$d_2 = 1 \times 10^{-12}$$

and

$$c_1 = 3.073 \times 10^7$$

The constants c_2 and d_1 are connected by the relation $c_2 = 4.965\ d_1$, so that if we adopt Paschen's value $d_1 = 2{,}921$

$$c_2 = 14{,}500$$

which is the value of c_2 most commonly employed.

15000—08——12

APPLICATION OF THE LAWS OF RADIATION AND TEMPERATURE TO THE CONDITIONS OF THE EARTH.

Imagine a spherical, perfectly conducting "black body" to be situated at a distance $\left(\frac{2.10}{1.32}\right)^{\frac{1}{2}}$ times the mean distance of the earth from the sun. Such a body would receive, like the earth, $1.32\pi R^2$ calories per minute, and, unlike the earth, would be at uniform temperature throughout. Let its absolute temperature be T. Then we shall have:

$$76.8\times10^{-12}\times4\pi R^2T^4=1.32\pi R^2$$

Whence:

$$T=256^{\circ}.0$$

Let us next inquire what, if any, change in the mean temperature of such a body would be introduced if, instead of being perfectly conducting, its substance should be of such a nature that the distribution of temperature over its surface would be similar to that of the earth. This distribution may be inferred from data selected by Arrhenius and quoted by Hann,[1] which are given in an abridged form in the following table. In computing the mean temperature (287°.2) at the earth's surface, the temperature of each zone is weighted in proportion to the area of the zone. There are then obtained the ratios of the actual temperatures of the zones to the mean temperature of the earth, and then the emission of a "black body" of a similar temperature distribution to the earth is compared with that of one of a uniform temperature equal to the mean temperature of the first. The procedure is self-explanatory.

Table 37.—*Mean temperature distribution upon the earth.*

I. Latitude	0°–20°	20°–30°	30°–40°	40°–50°	50°–60°	60°–90°	Sums.
II. Temperature	297°.8	293°.8	287°.9	281°.7	274°.6	266°.0	[1]287°.2
III. Area of zone	.342	.158	.143	.123	.100	.134	1.000
IV. Product II × III	101.9	46.4	41.2	34.6	27.5	35.6	....
V. Ratio of II to mean	1.037	1.023	1.002	.982	.957	.927	....
VI. Fourth power of V	1.156	1.095	1.008	.930	.839	.738	....
VII. Product III × VI	.395	.173	.144	.114	.084	.099	1.009

[1] Earth's mean temperature.

A "black body" of similar temperature distribution to that of the earth would emit therefore about 1 per cent more radiation than one of a uniform temperature equal to the mean temperature of the first; and a "black body" of uniform temperature must be one-fourth of 1 per cent above the mean temperature of the first to equal its emission. This difference is too small to be of importance in what follows, and will be neglected.

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[1] Meteorologie, p. 228.

MAXIMUM POSSIBLE VALUE OF THE "SOLAR CONSTANT."

It appears from the preceding statements that a perfect radiator at 256°.0 will emit as much radiation as the earth does. Since no other substance at the same temperature can emit as much radiation as the perfect radiator, but must be of a higher temperature in order to do so, it follows that the earth's mean temperature, 287°.2, differs from that of the perfect radiator emitting $1.32\pi R^2$ calories per minute, in the sense that it should do, if the mean value of the "solar constant" is 2.1 calories, as here determined. Suppose, however, that the "solar constant" had been taken as 3.5 calories or upward, in accordance with many of the published statements. Then if the albedo of the earth is 37 per cent, as here determined, the available radiation would be $2.20\pi R^2$ calories, and the corresponding temperature of the perfect radiator would be 290°.9, which is above the mean temperature of the earth. A black body at 287°.2 absolute would emit $2.09\pi R^2$ calories per minute. It appears therefore that either the "solar constant" is below $\frac{2.09}{0.63}=3.32$ calories, or else the albedo of the earth is above 37 per cent. This is true even if we regard the radiation of the earth as passing to space without obstruction from the radiating portion which is of highest temperature, namely, its solid and liquid surface, and if besides we regard that surface as equal in emissive power to the "black body."

RADIATING POWER OF THE EARTH.

We can by no means admit that the radiation from the solid and liquid surface of the earth passes unhindered to space. In the first place there are interposed the clouds, whose average presence includes 52 per cent of the time. These, because of the powerful absorption for rays of long wave-lengths of the water which composes them, are even more efficient screens to the radiation of the earth than they are to the radiation of the sun, so that during 52 per cent of the time we may regard the radiation of the surface of the solid and liquid earth to space as zero. During the remainder of the time, water vapor presents almost as effective a screen as the clouds, according to the observations of Rubens and Aschkinass.[1]

THE ABSORPTION OF WATER VAPOR FOR TERRESTRIAL RADIATION.

In order to appreciate the effect of water vapor on the radiation of the earth, it is necessary to know the distribution of the radiation of the earth in the spectrum. Inasmuch as no heat spectrum can exceed at any wave-length the intensity of the spectrum of a perfect radiator of the same temperature, it follows that an energy curve of a perfect radiator at 287°.2 will at any rate include the energy curve of the earth's solid and liquid surface. Such a curve has been computed by aid of

[1] Annalen de Physik und Chemie, vol. 64, p. 598, 1898.

Planck's formula, and its form is shown in line 2, Plate XX. The wave-lengths are given in microns, the ordinates in arbitrary units.

Line 3 of Plate XX is plotted in accordance with the observations of Rubens and Aschkinass, and represents the fractional transmission at long wave-lengths of an open tube 75 centimeters long, which was maintained at a temperature above 100° C. and continually supplied with steam from a side branch tube. A column of water vapor at atmospheric pressure 75 centimeters long and 1 centimeter in cross section, at 100° C. contains 0.0436 gram of water. If at a higher temperature its contents would of course be less.

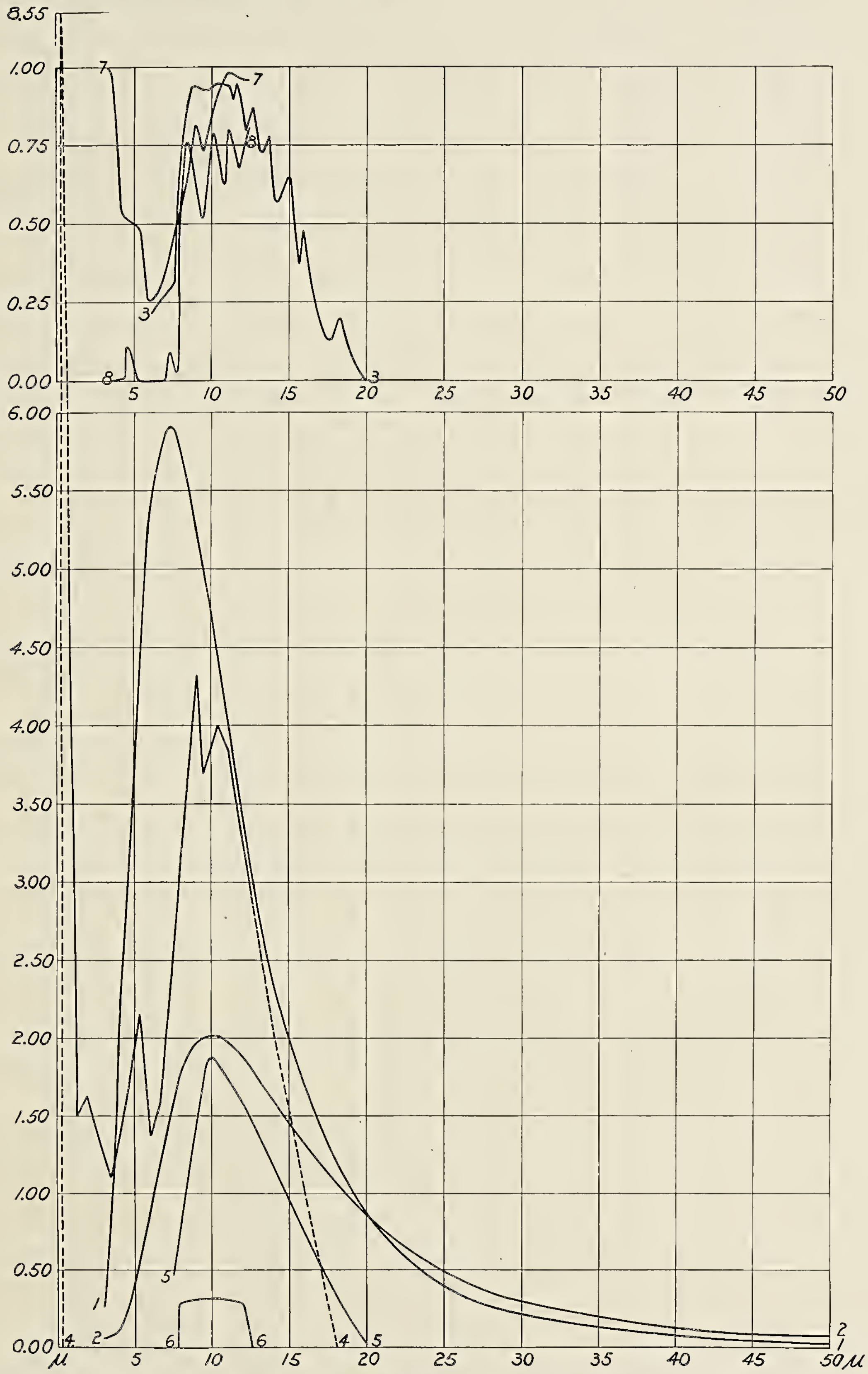
From the data collected by Arrhenius, and already employed in Chapter I of Part II, it may be shown that for the whole world the mean water-vapor contents of a vertical column of air 1 centimeter in cross section extending from sea-level to the limit of the atmosphere is 2.64 grams. Above the Mount Wilson level the quantity is 1.13 grams. Hence it follows that those rays which rise vertically from sea-level traverse a column of air containing an average of at least sixty times the amount of water vapor whose absorption was observed by Rubens and Aschkinass; and even above the Mount Wilson level the average water-vapor contents of the atmosphere in a vertical column is not less than twenty-six times that through which they observed.

Lines II and III of the following table give the intensity of the radiation of a "black body" at 287°.2, and the transmission observed by Rubens and Aschkinass; and in the fourth line the latter raised to the twenty-sixth power. The fifth and sixth lines give the transmission of the energy by one sixtieth and by about four-tenths, respectively, of the whole amount of water vapor in the earth's atmosphere. Curves corresponding to lines II, III, V, and VI are given also in Plate XX in lines 2, 3, 5, and 6.

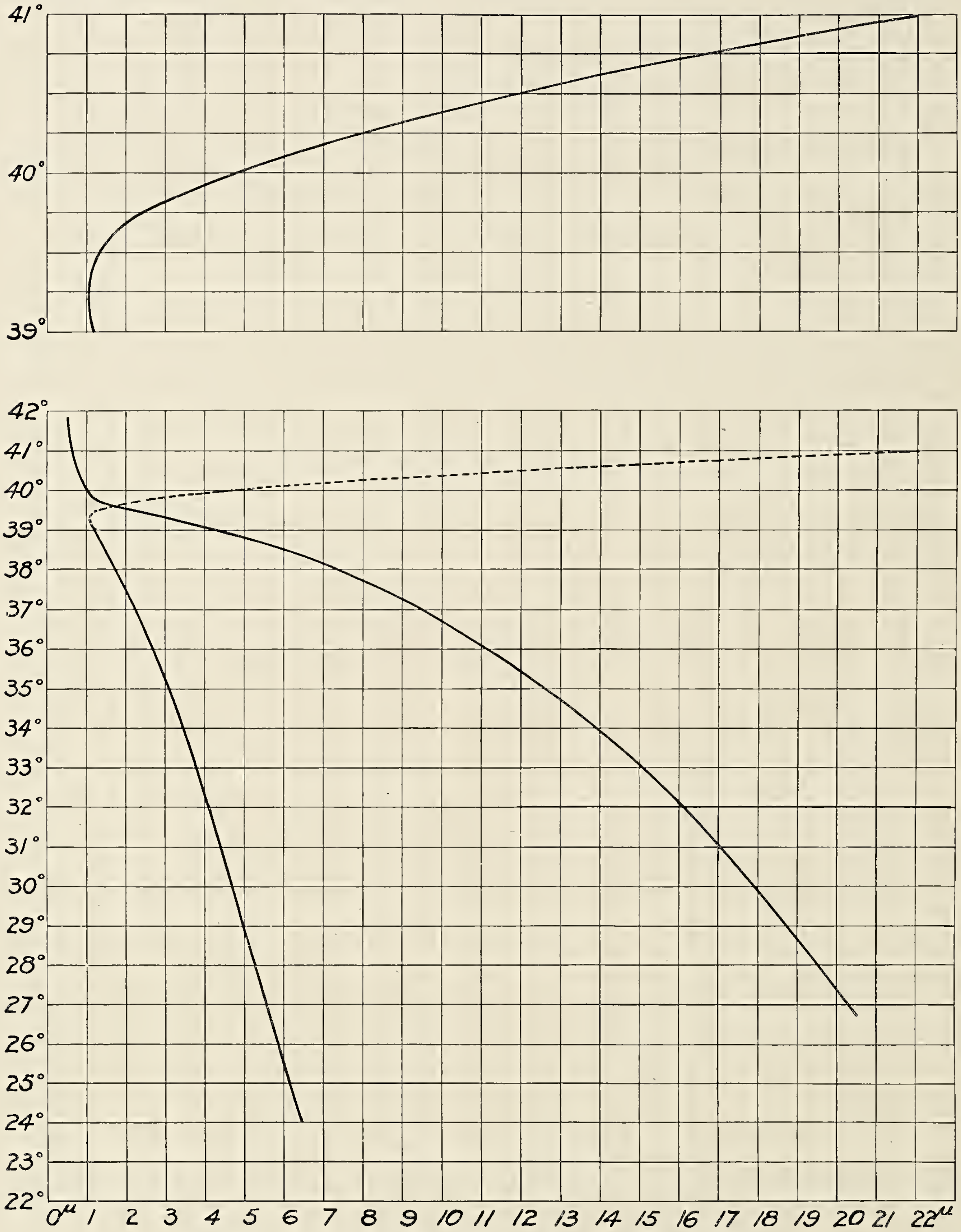
Table 38.—*Radiation and absorption at low temperatures.*

I. Wave-length	4μ	7.5μ	10μ	12.5μ	15μ	20μ	25μ	30μ	40μ	50μ
II. Intensity, Planck	0.10	1.55	2.01	1.81	1.44	0.84	0.48	0.29	0.12	0.068
III. Transmission, Rubens and Aschkinass	......	.37	.93	.82	.65	.01	......	......	......	......
IV. Twenty-sixth power of III	......	.000	.152	.006	.000	.000	......	......	......	......
V. Product II × III	......	.46	1.87	1.48	.94	.01	......	......	......	......
VI. Product II × IV	......	.00	.31	.02	.00	.000	......	......	......	......

By a summation of areas the comparative amounts of energy represented by lines 2, 5, and 6 of Plate XX have been determined, and the results are in the ratio of 152 to 64 to 5. If we should take these results as they stand, the conclusion would be that not more than 3½ per cent of the radiation starting at the



Radiation and Absorption at Low Temperatures.



Dispersion of 60° Rock-salt Prism, and Relation to Normal Spectrum.

level of Mount Wilson could reach space. But there are two considerations which tend to modify this conclusion. First, it is highly hazardous to extrapolate Rubens's and Aschkinass's results to any such extent as is here proposed, because it may probably be that the absorption of water vapor in this spectral region is made up of narrow bands of nearly complete absorption, separated by narrow bands of nearly perfect transmission, so that perhaps the introduction of additional water vapor would not in reality have increased the absorption very rapidly after all. Furthermore, it is barely possible that the water-vapor column through which Rubens and Aschkinass observed was so much more dense than that in the atmosphere that its absorption bands were broadened, owing to the great density of the absorbent, so that there was a stronger absorption than an equal amount of vapor would have produced if contained in a long column of less density. In the second place, it is to be noted that the data from which Arrhenius estimated the mean water-vapor contents of the atmosphere were obtained in all kinds of weather, and are not representative of exclusively fair weather conditions. But if we make all reasonable allowances for these considerations, it appears practically certain that no appreciable amount of radiation emitted by the earth can reach space except in a band included between wave-lengths 7μ and 20μ, and that the total amount of it is at any rate only a small fraction of that emitted by a "black body" of the size and temperature of the earth's surface.

Langley, in his paper on the Temperature of the Moon,[1] gives data of value in this connection. In Plate 6 of that publication he gives the vertical transmission of the atmosphere above Allegheny as determined by numerous observations of the moon at different zenith distances. He does not claim for this chart a high degree of accuracy, but merely states that such observation "permits us to give an approximate curve of transmission for the entire spectrum." In order to compare these results with those we have been discussing, it is necessary to change Langley's "Plate 6" to the normal wave-length scale.

For convenient reference there is given here in Plate XXI the approximate curve of deviation and wave-length of a 60° rock-salt prism and the curve for changing the intensities of the rock-salt prismatic spectrum to the normal scale. The steeper part of the latter curve is repeated on a more extended scale of deviation. To employ the intensity ratio curve, energy values in a 60° rock-salt prismatic curve are to be multiplied by the abscissa corresponding to the deviation given. Thus, at deviations 40° and 35°, multiply by 4.8 and 3.2, respectively. The same scale of abscissæ gives for the dispersion curve the wave-length in microns.

Plate XX, line 8, gives Langley's transmission curve on the normal scale. It appears at once by a comparison of lines 3 and 8 of Plate XX that Langley found

[1] Memoirs of the National Academy of Sciences, vol. 4, 9th Memoir.

absorption where Rubens and Aschkinass found it and in a greater amount than they did. Furthermore, Langley's band of complete absorption from 5.3μ to 7.2μ shows that there is no energy emitted to space by the earth's surface in the shorter wave-length part of the earth's spectrum not covered by the results of Rubens and Aschkinass.

Prof. E. F. Nichols in 1906 made measurements of the transmission of the atmosphere above Mount Wilson for solar rays at 51μ,[1] which show that the transmission there certainly does not exceed 3 per cent and more probably is nothing. This practically completes the proof that there is no radiation of the earth's surface to space excepting between wave-lengths 7μ and 20μ.

Langley published also in his paper on the Temperature of the Moon some measurements on the transmission of about 100 meters of air containing fairly well determined quantities of water vapor. These measurements consisted in the comparison of the total radiation of two blackened copper vessels filled with boiling water and placed at distances of 110 meters and 2 meters, respectively, from the observing apparatus. In each instance a blackened, ice-filled screen was the comparison body. Not only was the total radiation measured, but fortunately the spectrum of the body at 100 meters was also observed in comparison with the ice screen. These spectrum observations make it obvious that stray sunlight (probably reflected from the air) was present in considerable amount, and it will therefore be necessary to modify Langley's figures on this account.[2]

By means of the two curves of Plate XXI the spectrum of Langley's radiator at 110 meters has been reduced to the normal scale, as it appears in Plate XX, line 4. The dotted portions of line 4 are extrapolated by us. That portion of the extrapolation which includes the shorter wave-lengths is in accordance with the form of the solar energy curve at Washington for zenith sun. Probably the stray light in Langley's experiment was richer in blue light than the extrapolation shows, but it seemed better to err on the conservative side, if at all. Measurements have been made of the areas of the entire curve and of that part lying above 3.5μ, which is evidently sunlight; and it appears from the measurements that 22.1 per cent of the observed radiation came not from the radiator, but from the sun. At the time when these spectrum observations were being made the average amount of precipitable water in the path of the rays was 1.11 millimeters, as given by Langley, and by comparing with his measurements of total radiation made on other days it appears that with this amount of water vapor he would have observed 83 per cent as much radiation from the distant source as from the near one. Accordingly, the ratio of the stray light to the original amount of radiation was $83 \times 0.221 = 18.3$ per

[1] Contributions from the Solar Observatory, Mount Wilson, California, No. 19.

[2] It is sufficiently well known, of course, that a body at 100° C. emits no sensible fraction of its radiation at wave-lengths less than 4μ, while Langley found much radiation even at 1μ.

cent. We will now make the assumption that on each of the days when measurements of total radiation were made by him there was included in the amount of radiation attributed to the distant radiator some stray sunlight which amounted to 18.3 per cent of the original radiation of the distant source. Making this correction, we obtain the following results. The temperature at which water boils under the average barometric pressure observed during these experiments is about 99° C., and 2 degrees may be allowed for the cooling of the surface of the radiator by the air, making 370° as the absolute temperature of the source.

TABLE 39.—*Transmission from a blackened body at 370° to one at 273° through 100 meters of air.*

[Observers: Langley, Keeler, and Very.]

Date.	Precipitable water vapor present in grams per square centimeter cross section of column.	Percentage transmission (corrected for stray light).
1885.		
June 6	0.096	67.2
June 13	.151	60.9
June 15	.166	57.4
August 22	.205	48.7

On August 22, 1885, the amount of water vapor through which they observed was less than a tenth of the average amount which is present between sea-level and the outer limit of the atmosphere, so that it is obvious enough from these results that there can be very little radiation transmitted from the surface of the earth to space.

Curve 1 of Plate XX represents the transmission of a "black body" at 370° absolute to one at 273°, according to Planck's formula; and it is plotted on such a scale that the total area included under curve 4 is 83 per cent of that included under curve 1, in accordance with the general trend of the uncorrected results published by Langley. By this means it is easy to obtain a fair idea of the region of spectrum where the absorption took place, and what the amount of absorption was. By taking the ratios of the ordinates of curves 4 and 1 of Plate XX, transmission coefficients for the several wave-lengths have been computed, and these have been plotted as curve 7 of Plate XX. Omitting the part most influenced by stray sunlight, there is seen to be a pretty close agreement, both qualitatively and quantitatively, between the measurements published by Langley on the transmission of 0.111 gram of water vapor in a column 110 meters long and those of Rubens and Aschkinass for 0.0496 gram of water in a column 75 centimeters long. By measuring the areas under curves 4 and 1 of Plate XX, but omitting that portion of curve 4 lying to the left of 3.5μ, the average transmission for June 17 and 19, 1885, through 0.111 gram of water, appears to be 64.5 per cent, which is in good agreement with the general trend of the corrected results of the direct observations of the near and distant radiator.

From these latter a transmission of 65.4 per cent would be inferred for this amount of water.

From the combined work of Rubens and Aschkinass, Langley, Keeler and Very, and Nichols, we may then safely conclude that a tenth part of the average amount of water vapor in the vertical column of atmosphere above sea-level is enough to absorb more than half of the radiation of the earth to space, and it is highly probable that, considering the greater air mass attending the oblique passage of many of the rays to space, nine-tenths of the radiation of the solid and liquid surface of the earth is absorbed by the water vapor of the atmosphere even on clear days. On cloudy days none is transmitted, so that the average escape of radiation from the earth's surface to space probably does not exceed 5 per cent.

THE ABSORPTION OF CARBONIC-ACID GAS FOR TERRESTRIAL RADIATION.

Some writers have attributed a large share of the absorption of the atmosphere to the carbonic-acid gas which it contains, but though the experiments of Arrhenius [1] tended to show that carbonic-acid gas exercises a general absorption like water vapor, yet Ångström [2] and Koch [3] have shown that this is the case only when the carbonic acid is present in great density, and not, as in the atmosphere, when it is present in a long column of slight density. In atmospheric conditions the absorption of carbonic-acid gas in the spectrum of the earth appears to be confined to two bands extending from wave-length 3.6μ to 5.4μ, and from 13.0μ to 16.0μ, respectively.[4] In these bands its absorption is nearly total from 4.0μ to 4.8μ and from 14.0μ to 15.6μ, even when carbonic acid is present in much less quantities than the atmosphere contains. But the areas included by the energy curve of the "black body" at 287°.2 from 3.6μ to 5.4μ and from 13.0μ to 16.0μ are 0.5 per cent and 13.5 per cent of the total area of the curve, respectively; so that, as the earth has mainly a water surface which is doubtless practically "black," it appears that even in the absence of water vapor the total absorption possible by carbonic-acid gas would be 14 per cent. In all the lower regions of the atmosphere, however, water vapor is present in such quantities as almost completely to extinguish the radiation of the earth's surface in these two special regions, irrespective of the presence of carbonic-acid gas, and all the absorptive function of the latter worth considering, so far as the present evidence shows, must be exercised in the regions of the atmosphere higher than the altitudes to which water vapor extends in considerable quantities, or, in other words, above 5,000 [5] meters. Its effect there is merely to increase slightly the altitude of the layer which transmits radiation of two narrow spectral bands to space, and thus to decrease

[1] Annalen der Physik, vol. 4, p. 690, 1901.

[2] *Loc. cit.*, vol. 6, p. 172, 1901.

[3] Öfversigt af Kongl. Vetenskaps-Akademiens Förhandlingar, Stockholm, vol. 58, p. 391, 1901.

[4] See fig. 2 of the article of Ångström, Annalen der Physik, vol. 3, p. 720, 1900.

[5] See Hann, Meteorologie, p. 223.

slightly the temperature at which these wave-lengths are finally emitted. It therefore does not appear possible that the presence or absence, or increase or decrease, of the carbonic-acid contents of the air are likely to appreciably influence the temperature of the earth's surface.

These conclusions are in accord with those expressed by Ångström on this subject.[1]

THE SURFACE WHICH EMITS RADIATION FROM THE EARTH TO SPACE.

It seems to be certain, in view of what has been said, that the earth's solid and liquid surface, and the lower parts of the atmosphere, contribute directly almost nothing to the amount of radiation which the earth as a planet sends to space. The earth's surface and the lower atmosphere of course exchange radiation together, and by this process, and by convection, the heat of these regions ascends toward space. But convection grows less and less as the air becomes rarer, and must at length cease to be an appreciable factor. It is the water vapor and carbonic-acid gas far above the earth's surface, where the absorption of the rays by the water vapor and carbonic-acid gas lying still higher becomes small, that form the true radiating surface of the earth considered as a planet.

TEMPERATURE OF THE EARTH'S RADIATING LAYER.

We have seen that less than a tenth, possibly less than a twentieth of the total amount of water vapor in the atmosphere would be sufficient to absorb half of the radiation of a "black body" at a temperature of 287°.2 absolute; and the absorption would be nearly the same for radiating bodies between this temperature and 260°. If the experimental evidence both as to the temperature of the atmosphere and as to the radiation and absorption of water vapor and carbonic-acid gas were complete, it would be easy to compute what each layer of the atmosphere contributes to the radiation of the earth as a planet, and from this could be found the average temperature and emissive power of its radiating surface. But even with the scanty material at hand, and in consideration of the distribution of water vapor in the free air,[2] it seems safe to put the effective position of the radiating surface at fully 4,000 meters above sea-level.

In accordance with the statements of Hann[3] there appears to be no very great difference, depending on the latitude, in the rate of decrease of temperature in the free air with increasing altitude; and it will be not far from the truth to assign an average rate of 0°.6 C. per 100 meters for heights not exceeding 4,000 meters. In these circumstances we may make a horizontal reduction of the zone temperatures used in computing the mean temperature of the earth, and thus we

[1] Annalen der Physik, vol. 6, p. 173, 1901.

[2] Hann, Meteorologie, pp. 223, 274, 275.

[3] Hann, Meteorologie, pp. 155–159.

find at 4,000 meters a probable mean temperature of $287°.2-(40\times0°.6)=263°$. This temperature differs a little in the right direction from the temperature of a "black body" emitting $1.32\pi R^2$ calories per minute, which was found to be 256°.

A MAXIMUM VALUE OF THE "SOLAR CONSTANT."

We are now in a position to fix still closer the upper limit of probable values of the "solar constant." The temperature of the earth's radiating layer is, as just stated, not above 263°, and the radiation of a "black body" at 263° is $1.47\pi R^2$ calories per minute; so that the mean value of the "solar constant" can not be admitted to exceed $\frac{1.47}{1.00-0.37}=2.33$ calories per square centimeter per minute, even if water vapor is a perfect radiator, unless the albedo of the earth exceeds 0.37, or there is some fatal flaw in this train of reasoning based on the laws of radiation of a "black body" and the observed transmission of radiation by water vapor.

THE TEMPERATURE OF THE MOON.

Langley and Very have taken great pains to fix experimentally the probable temperature of the sunlit surface of the moon, and the latter concludes from his most recent revision of the evidence that the temperature near the subsolar point of the disk of the full moon is about 450° absolute.[1] The conditions at this point differ essentially from those at the earth's surface in several respects. First, there is no atmosphere to obstruct either income or outgo of radiation. Second, there is only a very slow rotation, so that the point in question has received sunlight steadily for a week. Third, the albedo for total radiation is not far, Mr. Very thinks, from one-eighth. Accordingly, employing the value 2.1 calories for the "solar constant," the temperature of a nonconducting "black body" surface under these conditions would be given as follows:

$$76.8\ T^4=\frac{7}{8}\times2.1\times10^{12}$$

$$T=394°$$

Coblentz[2] has lately shown that some of the materials likely to be prevalent on the moon's surface are very poor radiators at such temperatures as these, and this would tend to explain why Very has found a temperature so much higher than that of a "black body" under similar conditions. But there are indeed insuperable difficulties in determining experimentally the actual temperature of the moon's surface. Firstly, we do not know what its surface is composed of, and therefore have no means of discovering the relations which connect the lunar temperature and radiation. Secondly, the extremely great selective absorption of the water vapor in the earth's atmosphere prevents observers within several kilometers of sea-

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[1] Astrophysical Journal, vol. 8, p. 281, 1898.

[2] Investigations of Infra-red Spectra, Part IV, Carnegie Institution, 1906.

level from determining exactly either the total amount or the spectral distribution of the moon's radiation as it is actually emitted. Therefore, although we may fully agree with Mr. Very that the temperature of the moon's subsolar region exceeds very considerably that of the subsolar surface of the earth, yet, when quantitative work is proposed, there is not sufficiently exact data obtained or obtainable to enable us to determine the "solar constant" from the temperature of the moon.

SUMMARY OF CHAPTER IV.

The reflection of solar radiation to space by the various parts of the atmosphere and of the earth's surface is discussed, and we conclude that 37 per cent of solar radiation is reflected by the earth as a planet, and plays no part in warming or promoting life on the earth.

Of the 63 per cent of solar radiation absorbed by the earth as a planet, we conclude that 45 per cent, or a little more than two-thirds, is absorbed either at the earth's solid and liquid surface, or in the atmosphere within a mile of sea-level.

Adopting 2.1 calories per square centimeter per minute as the mean value of the "solar constant," we find that the rate of emission of radiation by the earth as a planet is 0.33 calorie per square centimeter per minute.

A perfect radiator at 256° absolute would emit radiation equal to 0.33 calorie per square centimeter per minute.

Since all natural bodies must fall short of the radiating power of the perfect radiator for equal temperatures, the radiating surface of the earth must be above the temperature 256° absolute.

The mean temperature of the earth's solid and liquid surface is 287°.2. If this be regarded as the radiating surface of the earth as a planet, then it is impossible that the mean value of the "solar constant" of radiation can exceed 3.32 calories unless the reflecting power or albedo of the earth exceeds 0.37, for otherwise the earth must be a better radiator than the "black body."

In fact, however, the solid and liquid surface of the earth is not its radiating surface, viewed as a planet; for the earth is cloudy 52 per cent of the time, and when clouds intervene, no terrestrial radiation can reach space from sea-level. Furthermore, the experiments of Rubens and Aschkinass, Langley, Keeler, Very, and Nichols indicate that the water vapor of the atmosphere is sufficient to absorb fully 90 per cent of the radiation arising from sea-level in cloudless weather. Hence not more than 5 per cent of the radiation of the earth's solid and liquid surface reaches space.

The true radiating surface of the earth as a planet is chiefly the water vapor of the atmosphere at an elevation of 4,000 meters or more above sea-level.

Carbonic-acid gas plays a very subordinate part, as compared to water vapor, in determining the earth's temperature.

This radiating layer may be regarded as of nearly perfect radiating power. Its temperature is about 263° absolute, and accords well with the values of the "solar constant" and the earth's albedo, which have been determined here.

In view of these facts the maximum value allowable for the mean value of the "solar constant" is 2.33 calories per square centimeter per minute. The assumption of a higher value than this requires us to suppose either that water vapor is a better radiator than the "black body," or else that the albedo of the earth exceeds 0.37.

The temperature of the moon, according to Very's figures, is in reasonable accord with the preceding statements.

Chapter V.

VARIATIONS OF SOLAR RADIATION AND THEIR EFFECTS ON THE TEMPERATURE OF THE EARTH.

VARIATION OF SOLAR RADIATION.

It has been shown to be the most probable conclusion from the work described in Part I that while the average intensity of the solar radiation outside the atmosphere is about 2.1 calories per square centimeter per minute there appear to be considerable departures from this mean value. For example, it appears from observations made at Washington in the winters of 1903, 1904, 1905, and 1906, respectively, that there have been several intervals when the "solar-constant" values were of the order of 2.20 calories, but in none of these instances did it appear that the duration of the period of high values exceeded two months. The great majority of the values obtained on Mount Wilson in the summer and autumn of 1905 and 1906 ranged between 2.00 and 2.10 calories, but they were at times as low as 1.94 calories and again as high as 2.14 calories. Departures of nearly 5 per cent and return were many times noted in the Mount Wilson values within periods of ten days. Besides these, a more gradual fluctuation of nearly 4 per cent was noted in the Mount Wilson work of 1905, requiring several months for the departure and return.

So far as the evidence presented can show, it is thought that many of these apparent changes of solar radiation are probably really due to changes in the sun. A fuller account of the different kinds of evidence as to the soundness of the work and the reasonableness of this conclusion is given in Part I, but a brief summary follows:

1. So far as the accuracy of the results depends on measurements at the surface of the earth, it appears that a fluctuation of 1 per cent exceeds the error of relative measurements from day to day.

2. The means of estimating the transmission of the atmosphere by the aid of the bolometer and spectroscope requires no improbable assumptions; and for much of the Mount Wilson work the accuracy of the means of estimation is apparently about 1 per cent, and is verified by the exactness with which the bolometric observations tally with the formula of extrapolation.

3. While Washington observations do not usually present such satisfactory evidences of an unvarying transparency of the air, some days of observation stand well in this respect; and it is found that the "solar-constant" results obtained at Washington on the best days show a close agreement with the values determined nearly simultaneously at Mount Wilson, although the stations are separated by 3,000 miles in longitude and 1 mile in altitude, and although the direct radiation observed at the surface of the earth is almost one-third greater on Mount Wilson than at Washington.

4. It is a necessary consequence of the ellipticity of the earth's orbit that the intensity of solar radiation outside the atmosphere should increase from July to January, and vice versa. The rate of increase during September and October is most rapid, and the total change during these months is over 3 per cent. In both 1905 and 1906 this real change of solar radiation was distinctly shown by the "solar-constant" observations on Mount Wilson, and this fact tends to strengthen our confidence in the other changes shown.

5. The observed mean temperature of the earth accords with the conclusion that the mean "solar constant" is 2.1 calories. We have found that the earth reflects away about 37 per cent of the radiation which the sun sends it, thus leaving but $1.32\pi R^2$ gram calories per square centimeter per minute available to warm the earth, if we assume the mean "solar constant" to be 2.1 calories. It is further shown that only a very small proportion of the radiation emitted by the earth's surface can reach space, because of the interposition of clouds and water vapor, so that the real surface which communicates the earth's heat to space is the water-vapor and carbonic-acid layer lying perhaps 4,000 meters above sea-level. The temperature of this layer is about 263° above absolute zero, and if it radiated as well as the most perfect radiator which can be imagined, the earth could not part with more than $1.47\pi R^2$ gram calories per minute. Accordingly, unless the albedo of the earth exceeds 37 per cent, the maximum value which can be fixed for the average "solar constant" is $\frac{1.47}{1.32}\times 2.1 = 2.33$ calories, and this departs no more from the assumed value, 2.1 calories, than can reasonably be explained as due to the imperfect radiating power of water vapor and carbonic acid, and the obstruction of the vapors lying above 4,000 meters in elevation.

6. The numbers and magnitudes of the fluctuations of "solar-constant" values obtained on Mount Wilson are not in the relation given by the laws of probability, as they should be if mere accidental error was responsible for them.

All these and other pieces of evidence thus tending to confirm the accuracy of the "solar-constant" observations and the conclusion that the intensity of solar emission varies considerably there remains to be considered what effects upon the climate of the earth, and especially upon its temperature, ought to follow from the supposed variations of solar radiation, and whether such consequences may be recognized in the records of past temperatures.

THE DEPENDENCE OF TERRESTRIAL TEMPERATURE ON SOLAR RADIATION.

By the "temperature of the earth" we name a thing which differs from place to place, depending on latitude, elevation, the distribution of water, foliage, etc.; and which differs from time to time, depending on the rotation of the earth, the declination of the sun, the distance of the sun, the capacity of the earth's material for heat, and other causes. The march of this complex phenomenon can not yet be minutely predicted by the application of general laws of physics, and since its minute details must be studied by statistical rather than analytical methods, the results of such a study are chiefly empirical in their nature. Nevertheless, there are certain general laws which aid such a study, and one of these is the law of Stefan-Boltzmann, which states that the intensity of radiation of a "perfect radiator" is proportional to the fourth power of its absolute temperature, or as expressed in the preceding chapter:

$$J = \sigma T^4.$$

As already shown, all other bodies must be at a higher temperature than the perfect radiator in order to emit as much radiation as it does, and accordingly we find that the surface temperature of the earth exceeds by some 30° the temperature of equilibrium which a perfect radiator receiving $1.32\pi R^2$ calories of radiation (the amount not lost to the earth by reflection) would maintain. This considerable excess of temperature is to be expected, because the radiation of the earth to space is stopped by the vapors of the atmosphere; and the real radiating surface exposed to space comprises the water vapor and carbonic-acid vapor lying probably at least 4,000 meters above sea-level, whose mean temperature is not far from 260° absolute, and very nearly of the temperature which a perfect radiator would assume. We may then consider that the outer layers of the vapor constituents of the earth's atmosphere approximate the quality of a perfect radiator and that the surface of the earth is a body wrapped in an ill-conducting mantle, receiving heat directly from the sun with little hindrance and maintained about 30° above the temperature of the outer layer of its mantle, because the latter is but a slow conductor of heat and a strong absorber of terrestrial radiation.

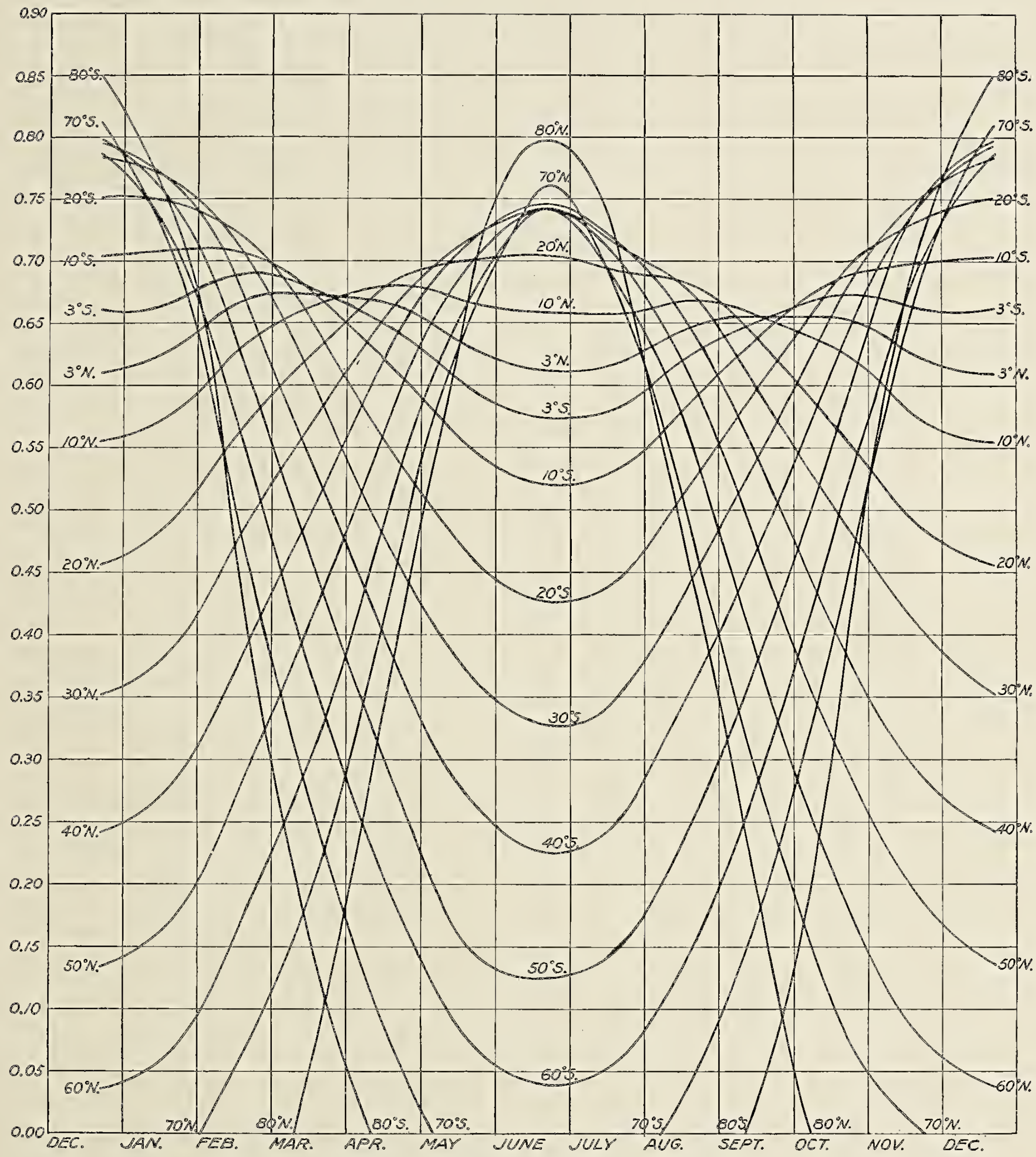
A first step toward finding the probable change of the temperature of the earth's surface which would follow a change in the radiation of the sun will therefore be taken if we find the change of temperature of the radiating layer of the atmosphere, or, what is nearly the same, the change of temperature of a perfect radiator at 260° corresponding to the proposed change in radiation. This is obtained by differentiating the expression of the Stefan-Boltzmann law and dividing the resulting differential equation by the original expression.

Thus we obtain:

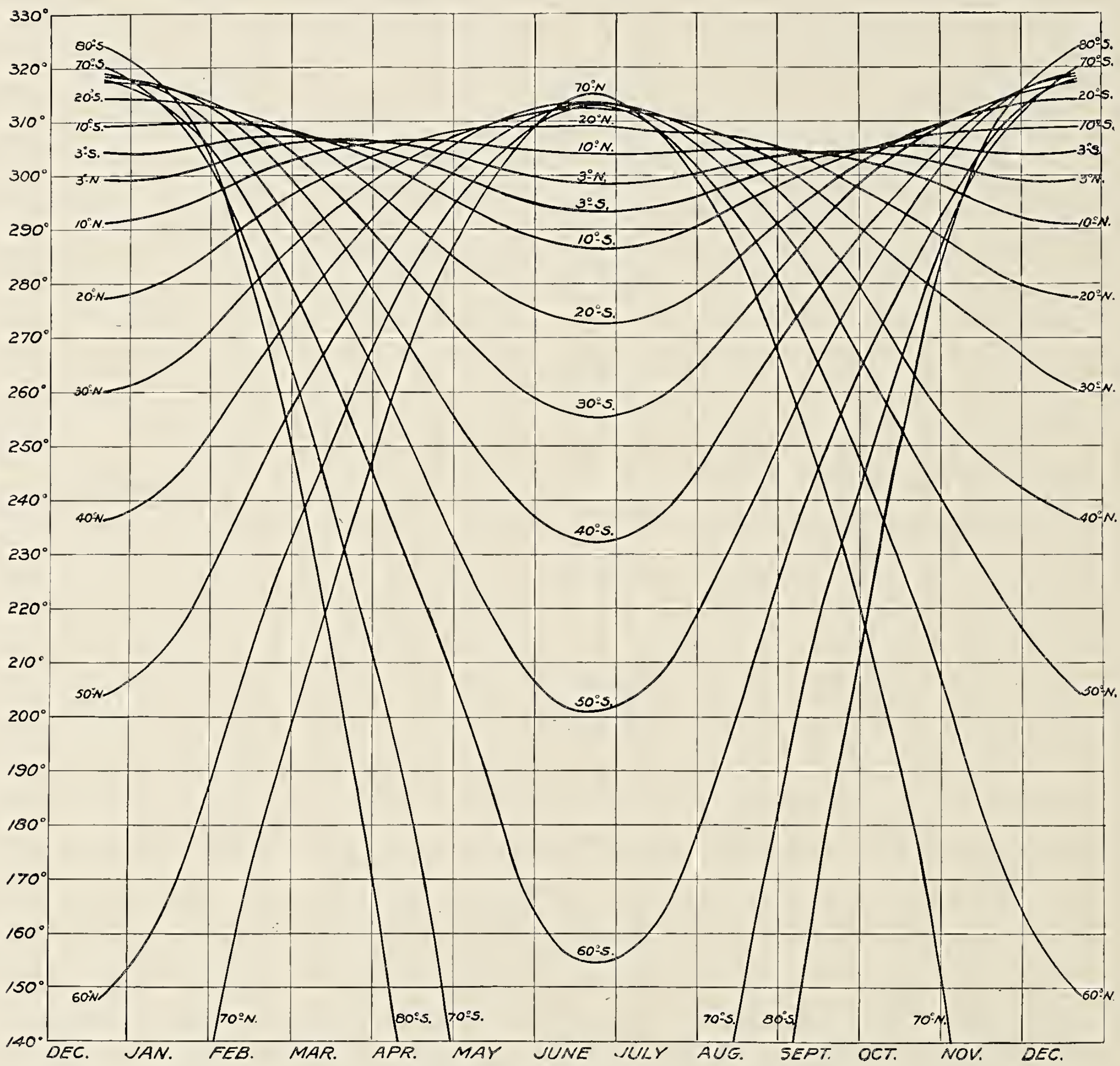
$$\frac{dT}{T}=\frac{1}{4}\frac{dJ}{J}$$

Hence the fractional change of the absolute temperature of a perfect radiator is one-fourth the fractional change of radiation which accompanies it; and a change of temperature of 1° in a body at 260° absolute temperature would accompany a change of radiation of 1.5 per cent. This state of affairs we may suppose to represent fairly closely the conditions of the atmosphere at 4,000 meters height, provided the mean cloudiness of the earth remains substantially unchanged.

It by no means follows from this that every change of solar radiation of 1.5 per cent will produce 1° change in the temperature at the surface of the earth. For (1) the amount of solar radiation available to warm the earth depends on the reflecting power or albedo of the earth, and this depends on the cloudiness. The present mean albedo is estimated at 37 per cent, but if the mean cloudiness could be increased from the present value (52 per cent) to nearly double the present value, the albedo of the earth would rise to nearly 70 per cent, and thus the amount of radiation available to warm the earth would be reduced nearly half. There would not be much change in the radiating power of the earth as a planet if the cloudiness should be altered, because the principal radiating surface would remain the water vapor above the clouds as before, and therefore the temperature of the earth would certainly fall if the cloudiness increased. Now, the presence of clouds might conceivably be altered by a change of solar radiation, both by a preliminary change of temperature of the atmosphere, and perhaps in more obscure ways, so that it is not certain that a change of 1.5 per cent in solar radiation would produce neither more nor less than 1.5 per cent change in the radiation available to warm the earth. (2) Since the earth's surface is about 30° warmer than its radiating layer, there is a margin of uncertainty whether the difference assumed to be 30° would be neither more nor less than 30° after an increase of 1.5 per cent in solar radiation. (3) In accordance with the laws of heat the change of temperature which would naturally result from any given change of conditions does not come to its maximum amount instantly, but there is a delay in the production of the full effect, depending on the capacity of the body for heat, and the readiness of heat communication from one part to another. Three-fourths of the surface of the earth is of water, the material which has the maximum capacity for heat of all common substances, and this material is also highly transparent to solar radiation, and besides is mixed freely by winds, rains, currents, and convection streams, so



Radiation Emitted by a "Hypothetical Earth."



Absolute Temperature of a "Hypothetical Earth."

that tremendous amounts of it are available to be affected by the changes of radiation. All the oceans exhibit a fall of temperature from the surface downward, and the minimum temperature is not reached at 1,500 fathoms below sea-level. This behavior contrasts strongly with what is found beneath the earth's land surface, and indicates that the ocean is in some degree under the influence of solar radiation even to such a depth as 1,500 fathoms, although the influence of radiation on land is hardly felt at 25 fathoms depth. The capacity of the oceans for the heat produced by solar radiation is so enormous that a considerable time must necessarily elapse before anything like the full effect of a solar change can make itself felt upon temperatures in those regions controlled largely by oceanic influences. Even upon the land there is a considerable capacity for heat. From these considerations it is therefore evident that the change of temperature which will attend any change of solar radiation of a given amount will be less the shorter the period over which the changed conditions prevail; and while a change of solar radiation having a period of several years' duration might be expected to produce nearly as great a change of temperature as if it continued forever, an equal change which ran its course to and fro in a few days or weeks would produce very much less change of temperature.

THE YEARLY FLUCTUATIONS IN TERRESTRIAL TEMPERATURES.

The three factors just considered—namely, cloudiness, efficiency of the atmospheric blanket, and capacity of the earth's surface for heat—will almost certainly have different effects in different localities. A study of yearly fluctuations of temperature attending the change of declination of the sun will furnish some idea of the dependence of temperature in different localities on solar radiation, and that inquiry will be promoted by introducing the conception of "a hypothetical earth" whose temperature may be computed. Imagine a thin spherical shell of matter perfectly absorbing and perfectly radiating, and having the size, position, and motions of the earth, but having perfect conductivity for heat along parallels of latitude, while perfectly nonconducting along meridians of longitude. The average amount of radiation falling upon and emitted by such a body in calories per square centimeter per minute, and the absolute temperature which it would have on different parallels of latitude and for all times of the year, are given graphically by Plates XXII and XXIII. The values of radiation are computed on the basis of a mean "solar constant" of 2.1 gram calories per square centimeter per minute, and the temperatures by the aid of the Stefan-Boltzmann formula, using Kurlbaum's value of the constant σ, namely, 76.8×10^{-12} gram calories per square centimeter per minute.

We know that for any change of the "solar constant" there would be an immediate change of temperature at every point upon the "hypothetical earth," amounting to one-fourth the fractional change of the radiation. For reasons already stated, it is not to be expected that the change of temperature of any meteorological station on the real earth's surface corresponding to a given change of solar radiation of short period, will be as great in its magnitude as the corresponding change of temperature which would occur at a corresponding point on the "hypothetical earth" under the same influences. But it does seem probable that for solar changes of a period of a few months' duration, the change of temperature to be expected at a given meteorological station will bear about the same ratio to the computed change of temperature at a corresponding point of the "hypothetical earth" that the annual range of temperature of the said meteorological station bears to the annual change of temperature computed for the said point on the "hypothetical" earth. For solar radiation changes of a few days or weeks in period, the corresponding changes of temperature at the earth's surface will naturally be smaller in proportion to the cause, because of the great capacity of the earth for heat and the consequent lag in its reaction to changes of radiation. In the consideration of solar radiation changes of many years' period, on the other hand, the earth's capacity for heat will be a factor of small consequence; but any changes of cloudiness dependent on change of solar radiation will produce their normal effects.

The following Table 40 gives for 63 stations[1] the mean yearly range and lag of temperatures in comparison with the corresponding temperatures of the "hypothetical earth." In order to determine the lag, the mean monthly temperatures have been plotted, regarding the means as corresponding to the temperature of the fifteenth day of each month, and the positions of maxima and minima have been found on the smooth curve drawn through the monthly means.

The stations are arranged in the order of their latitude; there is given also the longitude and elevation; the maximum and minimum yearly temperatures with the times of their occurrence; the maximum and minimum temperatures of corresponding stations on the "hypothetical earth" and times of their occurrence; the range of temperatures of the real and hypothetical stations; the percentage ratio the former bears to the latter; and the lag of the temperature maxima and minima of the real stations behind the corresponding dates for the hypothetical stations. Immediately following the names of the stations are letters C, I, L, or LC, signifying, respectively, Coast, Small Island, Interior Land, or Inland Sea-coast stations. In the last column are letters R and symbols * and **, whose significance will be understood from what follows.

[1] For temperatures see Hann Lehrbuch der Meteorologie, edition of 1901, p. 92; also edition of 1906, Appendix; and Hann Tägliche Gang der Temperatur Inneren Tropenzone, 1903, Table VI.

TABLE 40.—*Yearly range of temperature at 63 stations.*

Station.	Island, coast, or land.	Latitude.	Longitude.	Elevation.	Maximum.		Minimum.		Temperature range.		Temperature lag.		Group.
					Temperature absolute.	Date.	Temperature absolute.	Date.	In degrees.	In percentage of "hypothetical."	Of maximum.	Of minimum.	
		° ′	° ′	*Meters.*	°		°				*Days.*	*Days.*	
Godthaab	C.	64 11 N.	51 46 W.	11	280.2	Aug. 1	262.4	Jan. 10	17.8	7.2	40	19	R
"Hypothetical"					314.0	June 21	67.0	Dec. 21	247.0				
Thorshaven	I.	62 2	6 44 W.	9	284.0	Aug. 1	275.2	Jan. 15	8.8	4.1	40	56(?)	R
"Hypothetical"					314.0		100.0	Mar. 15	214.0				
Jakutsk	L.	62 1	129 43 E.	100	292.0	July 18	240.0	Jan. 10	52.0	24.3	27	19	*
"Hypothetical"					314.0		100.0		214.0				
St. Petersburg	LC.	59 56	30 16 E.	6	290.7	July 18	263.6	Jan. 24	27.1	14.7	27	34	R
"Hypothetical"					314.0		130.0	Dec. 21	184.0				
Christiania	LC.	59 55	10 43 E.	25	290.1	July 21	268.4	Feb. 5	21.7	11.8	30	45	R
"Hypothetical"					314.0		130.0		184.0				
Tomsk	L.	56 30	84 58 E.	122	291.7	July 18	253.4	Jan. 17	38.3	24.9	27	26	*
"Hypothetical"					314.0		160.0	Dec. 22	154.0				
Irkutsk	L.	52 16	104 19 E.	490	291.4	July 18	252.2	Jan. 15	39.2	31.4	27	23	*
"Hypothetical"					314.0		189.0	Dec. 23	125.0				
Valentia (West Ireland)	C.	51 54	10 18 W.	7	288.1	Aug. 12	280.1	Jan. 1	8.0	6.5	52	9	R
"Hypothetical"					314.0		191.0		123.0				
Uralsk	L.	51 43	50 55 E.	109	295.1	July 18	256.6	Jan. 18	38.5	31.8	27	26	*
"Hypothetical"					314.0		193.0	Dec. 23	121.0				
Winnipeg	L.	49 53	97 7 W.	233	291.9	July 15	251.4	Jan. 21	40.5	36.9	24	28	*
"Hypothetical"					314.0		204.0	Dec. 24	110.0				
Paris	L.	48 50	2 20 E.	50	291.3	July 24	275.3	Jan. 12	16.0	15.2	33	19	R
"Hypothetical"					314.0		209.0		105.0				
Victoria (British Columbia)	C.	48 24	123 19 W.	26	288.9	July 31	276.1	Jan. 18	12.8	12.3	40	25	R
"Hypothetical"					314.0		210.0		104.0				
Budapest	L.	47 30	19 2 E.	153	294.3	July 18	270.9	Jan. 15	23.4	23.4	27	22	*
"Hypothetical"					314.0		214.0		100.0				
Montreal	L.	45 30	73 35 W.	57	293.5	July 15	262.1	Jan. 15	31.4	34.1	24	22	*
"Hypothetical"					314.0		222.0		92.0				
Taschkent	L.	41 20	69 18 E.	480	300.2	July 18	272.3	Jan. 27	27.9	34.9	27	34	*
"Hypothetical"					314.0		234.0		80.0				
Madrid	L.	40 24	3 42 W.	655	298.0	July 28	277.1	Dec. 31	20.9	26.8	37	7	*
"Hypothetical"					314.0		236.0		78.0				
Peking	L.	39 57	116 28 E.	38	299.0	July 18	268.3	Jan. 15	30.7	23.6	27	22	*
"Hypothetical"					314.0	June 21	237.0		77.0				
Denver	L.	39 45	105 0 W.	1,613	295.2	July 21	270.9	Jan. 18	24.3	32.0	34	25	*
"Hypothetical"					314.0	June 20	238.0		76.0				
St. Louis	L.	38 38	90 12 W.	173	299.0	July 24	272.2	Jan. 18	16.8	23.3	34	25	*
"Hypothetical"					314.0		242.0		72.0				
Athens	LC.	37 50	23 43 E.	107	300.2	July 28	280.9	Jan. 20	19.3	27.0	38	27	*
"Hypothetical"					313.6		242.2		71.4				

Table 40.—*Yearly range of temperature at 63 stations*—Continued.

Station.	Island, coast, or land.	Latitude.	Longitude.	Elevation.	Maximum.		Minimum.		Temperature range.		Temperature lag.		Group.
					Temperature absolute.	Date.	Temperature absolute.	Date.	In degrees.	In percentage of "hypothetical."	Of maximum.	Of minimum.	
		° ′	° ′	*Meters.*	°		°				*Days.*	*Days.*	
Ponta Delgada (Azores)	I.	37 45	25 32 W.	20	295.0	Aug. 14	286.9	Feb. 15	8.1	11.4	55	53	R
"Hypothetical"					313.6		242.8		70.8				
Tokyo	C.	35 41	139 45 E.	21	298.4	Aug. 3	275.6	Jan. 18	22.8	34.5	44	25	R
"Hypothetical"					313.5		247.4		66.1				
Leh	L.	34 10	77 42 E.	3,510	289.4	July 28	265.6	Jan. 18	23.8	38.3	38	25	*
"Hypothetical"					313.3		251.2		62.1				
Bagdad	L.	33 20	44 26 E.	72	307.1	Aug. 2	282.4	Jan. 15	24.7	41.0	43	22	R
"Hypothetical"					313.2	June 20	253.0		60.2				
Charleston (S.C.)	C.	32 47	79 56 W.	15	300.8	July 24	283.0	Jan. 15	17.8	30.0	35	22	*
"Hypothetical"					313.0	June 19	254.0	Dec. 24	59.0				
San Diego	C.	32 43	117 10 W.	27	293.6	Aug. 18	285.0	Jan. 18	8.6	14.6	60	25	R
"Hypothetical"					313.1	June 19	254.0		59.1				
Wadi Halfa	L.	21 55	31 19 E.	128	305.8	July 1	288.2	Jan. 15	17.6	49.6	21	23	*
"Hypothetical"					309.9		274.4		35.5				
Honolulu	I.	21 18	157 50 W.	15	298.4	Aug. 15	294.3	Jan. 18	4.1	12.0	66	26	R
"Hypothetical"					309.7	June 10	275.4	Dec. 23	34.3				
Nagpur	L.	21 9	79 11 E.	333	307.7	May 9	292.0	Dec. 28	15.7	46.3	−32	5	R
"Hypothetical"					309.5	June 10	275.6	Dec. 23	33.9				
Mexico	L.	19 26	99 8 W.	2,278	291.1	May 6	284.9	Dec. 28	6.2	20.3	−32	6	R
"Hypothetical"					309.0	June 7	278.4	Dec. 22	30.6				
Port au Prince	C.	18 34	72 21 W.	36	300.6	July 18	297.1	Jan. 15	3.5	12.1	44	24	R
"Hypothetical"					308.6	June 4	279.6		29.0				
Timbuktu	L.	16 49	2 52 W.	250	308.4	May 28	294.2	Dec. 28	14.2	55.7	3	6	**
"Hypothetical"					307.7	May 25	282.2	Dec. 22	25.5				
St. Louis	C.	16 1	18 31 W.	5	301.1	Sept. 15	293.2	Feb. 1	7.9	32.8	86	41	R
"Hypothetical"					307.5	May 22	283.4	Dec. 22	24.1				
Manila	LC.	14 34	127 11 E.	14	301.6	May 15	297.9	Jan. 15	3.7	17.1	0	24	R
"Hypothetical"					307.0	May 15	285.4	Dec. 22	21.6			19	
Manila					300.2	Aug. 15	300.0	July 20			14		
San Jose de Costa Rica	L.	9 56	84 4 W.	1,170	293.5	May 10	291.7	Jan. 7	1.8	12.4	8	12	R
"Hypothetical"					306.0	May 2	291.5	Dec. 20	14.5				
San Jose					292.8	Sept. 12	292.7	Aug. 24	0.1	6.2	23	54	
"Hypothetical"					305.5	Aug. 20	303.9	July 1	1.6				
Colombo	C.	6 56	79 52 E.	13	300.8	May 1	298.4	Jan. 1	2.4	22.3	24	12	R
"Hypothetical"					306.0	Apr. 7	295.2	Dec. 20	10.8				
"Hypothetical"					304.0	Sept. 10	302.3	July 1	1.7				
Jaluit	I.	5 55	169 40 E.	3	300.2	Feb. 12	300.0	Dec. 15	0.2	2.1	−50	−4	R
"Hypothetical"					305.9	Apr. 3	296.2	Dec. 19	9.7				
Jaluit					300.1	Nov. 1	299.8	July 1	0.3	9.0	47	0	
"Hypothetical"					305.0	Sept. 15	301.6	July 1	3.4				
Lado	L.	5 2	31 44 E.	465	303.0	Mar. 12	298.1	Aug. 20	4.9	58.3			R
"Hypothetical"					305.7	Apr. 17	297.3	Dec. 19	8.4				
"Hypothetical"					303.8	Sept. 22	300.7	July 1	3.1				

TABLE 40.—*Yearly range of temperature at 63 stations*—Continued.

Station.	Island, coast, or land.	Latitude.	Longitude.	Elevation.	Maximum.		Minimum.		Temperature range.		Temperature lag.		Group.
					Temperature absolute.	Date.	Temperature absolute.	Date.	In degrees.	In percentage of "hypothetical."	Of maximum.	Of minimum.	
		° ′	° ′	*Meters.*	°		°				*Days.*	*Days.*	
Kamerun	C.	4 2 N.	9 42 E.	12	299.6	Feb. 15	296.7	Aug. 6	2.9	38.6			R
"Hypothetical"					305.5	Mar. 25	298.0	Dec. 18	7.5				
"Hypothetical"					303.8	Sept. 25	300.0	July 1	3.8				
Quito	L.	0 14 S.	78 32 W.	2,860	286.0	Feb. 15	285.7	Oct. 1	0.3	7.5			R
"Hypothetical"					306.0	Mar. 5	302.0	Dec. 16	4.0				
Quito					285.8	May 18	285.6	Apr. 12	0.2	5.0			
					286.0	Aug. 18	285.6	June 30	0.4				
"Hypothetical"					304.9	Oct. 15	297.0	June 30	7.9				
Para	C.	1 27	48 29 W.	10	299.4	Nov. 12	298.7	July 15	0.7	31.8	25	15	R
"Hypothetical"					305.4	Oct. 18	303.2	Dec. 15	2.2				
Para					298.9	June 1	298.0	Feb. 15	1.9	18.6	91	62	
"Hypothetical"					306.0	Mar. 1	295.6	June 30	10.4				
Kwai	L.	4 45	38 18 E.	1,610	291.9	Feb. 6	286.4	July 15	5.5	36.0	−11	15	**
"Hypothetical"					307.9	Feb. 17	292.6	June 30	15.3				
Quixeramobim	L.	5 16	39 16 W.	207	301.6	Dec. 15	300.0	July 3	1.6	10.0	−63	3	R
"Hypothetical"					308.0	Feb. 16	292.0	June 30	16.0				
Batavia	C.	6 11	106 50 E.	7	299.4	May 12	298.7	July 15	0.7	6.6			R
					299.4	Oct. 12	298.3	Jan. 30	1.1				
"Hypothetical"					308.1	Feb. 16	291.2	June 28	16.9				
Dar-es-Salam	C.	6 49	39 18 E.	13	300.8	Jan. 20	296.2	Aug. 1	4.6	25.7	−21	34	R
"Hypothetical"					308.4	Feb. 10	290.5	June 28	17.9				
Loanda	C.	8 49	13 7 E.	59	299.0	Feb. 20	292.9	Aug. 15	6.1	29.5	17	48	*
"Hypothetical"					309.1	Feb. 3	288.4	June 28	20.7				
Lima	L.	12 4	77 1 W.	158	296.3	Feb. 12	289.1	July 25	7.2	27.5	23	28	*
"Hypothetical"					310.5	Jan. 20	284.3	June 27	26.2				
Point Darwin	C.	12 28	130 51 E.	21	302.2	Nov. 4	296.7	July 18	5.5	20.4	−77	21	R
"Hypothetical"					310.8	Jan. 20	283.8	June 27	27.0				
Apia	I.	13 49	171 45 W.	4	299.2	Dec. 20	298.1	Aug. 1	1.1	3.8	−30	34	R
"Hypothetical"					311.5	Jan. 11	282.2	June 27	29.3				
St. Helena	I.	15 57	5 41 W.	540	292.3	Mar. 28	286.8	Sept. 6	5.5	16.6	80	71	R
"Hypothetical"					312.4	Jan. 7	279.3	June 27	33.1				
Arequipa	L.	16 24	71 30 W.	2,360	287.6	Jan. 15	282.6	June 15	5.0	14.7	9	−12	R
"Hypothetical"					312.6	Jan. 6	278.7	June 27	33.9				
Mauritius	I.	20 6	52 33 E.	54	298.7	Feb. 1	293.1	Aug. 1	5.6	13.8	31	36	R
"Hypothetical"					314.0	Jan. 1	273.4	June 25	40.6				
Rio de Janeiro	C.	22 54	43 10 W.	66	298.4	Feb. 12	292.9	July 15	5.5	11.8	46	20	R
"Hypothetical"					315.2	Dec. 28	268.5	June 25	46.7				
Walfischbai	C.	22 56	14 26 E.	3	292.0	Mar. 18	286.8	Aug. 24	5.2	11.1	80	60	R
"Hypothetical"					315.2	Dec. 28	268.5	June 25	46.7				
Alice Springs	L.	23 38	133 37 E.	587	302.9	Jan. 24	283.9	July 12	19.0	39.4	28	17	*
"Hypothetical"					315.5	Dec. 27	267.3	June 25	48.2				
Brisbane	C.	27 28	153 6 E.	43	297.5	Dec. 31	287.2	July 9	10.3	18.3	6	15	**
"Hypothetical"					316.6	Dec. 25	260.3	June 24	56.3				
Kimberley	L.	28 42	24 27 E.	1,232	297.8	Jan. 1	282.7	July 6	15.1	25.7	8	9	**
"Hypothetical"					317.0	Dec. 24	258.3	June 23	58.7				

TABLE 40.—*Yearly range of temperature at 63 stations*—Continued.

Station.	Island coast, or land.	Latitude.	Longitude.	Elevation.	Maximum.		Minimum.		Temperature range.		Temperature lag.		Group.
					Temperature absolute.	Date.	Temperature absolute.	Date.	In degrees.	In percentage of "hypothetical."	Of maximum.	Of minimum.	
		° ′	° ′	*Meters.*	°		°				*Days.*	*Days.*	
Durban	C.	29 51	31 0 E.	79	298.2	Feb. 9	291.1	July 3	7.1	11.6	47	10	R
"Hypothetical"					317.4	Dec. 24	256.0	June 23	61.4				
Cordoba	L.	31 25	64 12 W.	439	296.2	Jan. 28	282.2	June 26	14.0	21.6	31	3	*
"Hypothetical"					317.8	Dec. 23	253.0	June 23	64.8				
Santiago	L.	33 27	70 40 W.	519	292.6	Jan. 6	280.2	July 1	12.4	17.7	15	8	**
"Hypothetical"					318.5	Dec. 22	248.4	June 23	70.1				
Buenos Aires	C.	34 37	58 21 W.	22	297.3	Jan. 26	283.0	July 3	14.3	19.4	36	10	*
"Hypothetical"					318.9	Dec. 22	245.2	June 23	73.7				
Adelaide	C.	34 57	138 35 E.	43	296.4	Jan. 15	283.7	July 18	12.7	16.9	24	25	*
"Hypothetical"					319.0	Dec. 22	244.8	June 23	75.2				
Punta Arenas	LC.	53 10 S.	70 54 W.	21	284.1	Jan. 28	273.9	July 12	10.2	7.6	38	18	R
"Hypothetical"					319.0	Dec. 21	185.0	June 24	134.0				

There are included in the foregoing tables 7 small island, 21 coast, 30 inland, and 5 inland sea-coast stations. The average result of the comparison of the temperatures of these stations with those of the "hypothetical earth" is as follows:

	Percentage range.	Lag maximum days.	Lag minimum days.	Lag number.[1]
I	8	57	40	2
C	20	44	24	5
LC	27	25	25	1
L	29	26	18	7

If there were available the normal temperatures of all these 63 stations, and the departures by days or months from these normal temperatures, it might occur to the student of solar radiation to see if there occurred simultaneously at all these stations departures from the mean temperatures, indicating a common cause at work independent of position on the earth, and which could be assumed to be a variability of the sun. But the tables just given show that before proceeding in such a quest he should reject over half of these stations. For in some stations of nearly equal latitude, as Batavia and Dar-es-Salam, for example, the same annual change of insolation produces a nearly opposite fluctuation of temperatures, and in other stations whose behavior is less extremely different than these, the lag of temperature change behind the change of insolation that produces it differs by weeks or months; so that there is no reason to expect that any given fluctuation of solar radiation will simultaneously produce a temperature effect of the same kind all over the world.

[1] Number stations lag doubtful or strongly negative. These stations are excluded in obtaining two preceding columns.

In general, those stations would be regarded as best for such a statistical inquiry as to a possible variation of solar radiation in which the temperature ranges followed in amount and time most closely to those of the corresponding stations on the "hypothetical earth," but the amount of range is of less importance than the smallness of lag. Of the stations given, the five followed by the symbol ** best suit these requirements. Twenty-two others with the symbol * are found to be very nearly comparable to one another in these respects, and fall but little behind the first five. The remaining 36 stations marked R are so tardy or indefinite in their response to changes of insolation that they should be rejected, as likely to confuse or nullify any true result which the others might indicate.

In the following table is a summary of the stations thus classified:

Character.	Number of stations.				Per cent range.	Lag in days.		Average deviation of columns—		
	I.	C.	LC.	L.		Maximum.	Minimum.	6.	7.	8.
**	0	1	0	4	30.7	4.2	10.6	12.1	6.6	3.5
*	0	4	1	17	29.4	27.4	23.1	5.9	4.3	5.0
R	7	16	4	9	....	....	....	....	....	....

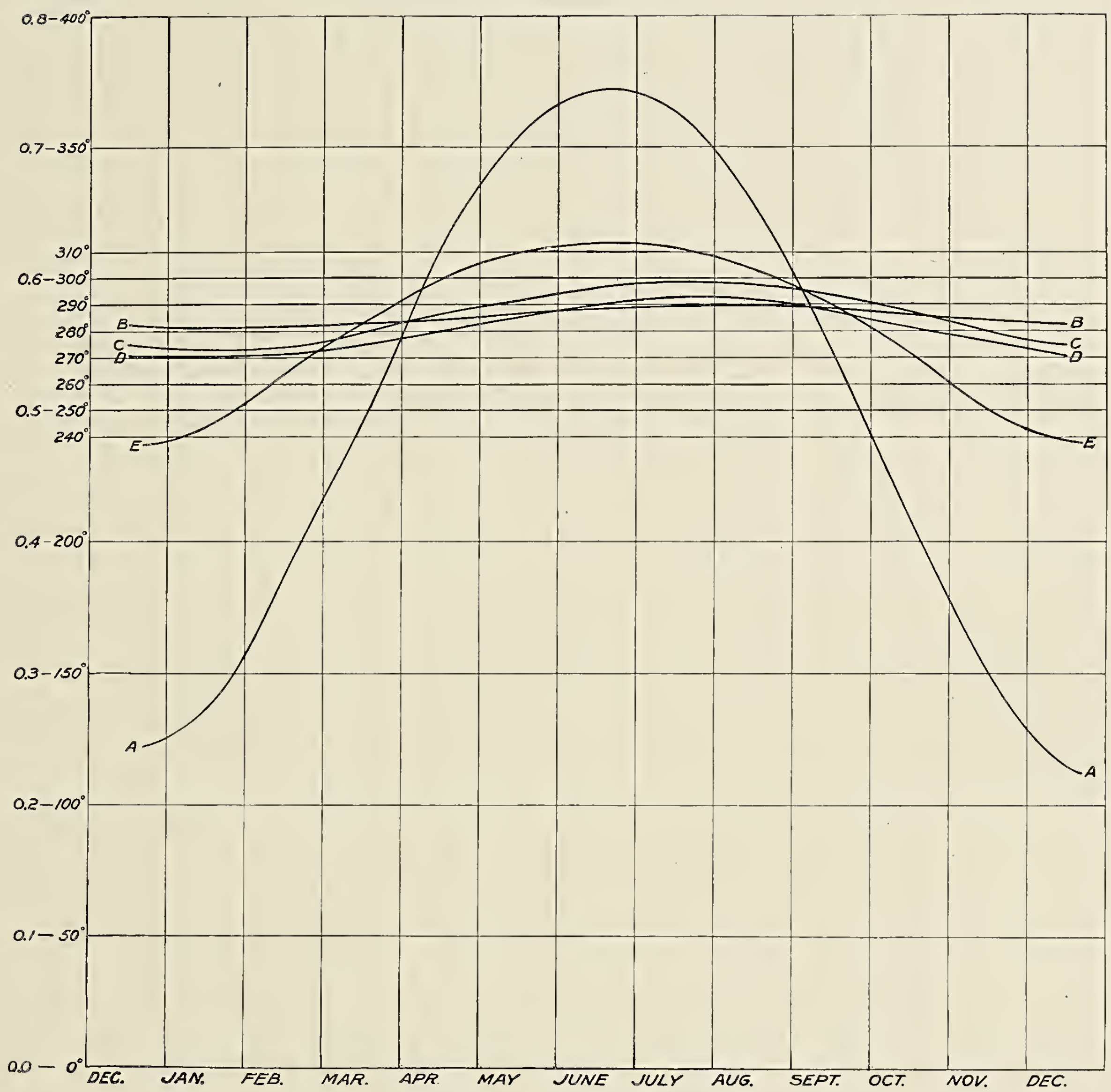
From the preceding tables it appears that stations of the first and second classes ought not to be combined together in a single statistical inquiry of the kind proposed on account of the conflict of their lag in response to solar fluctuations; but either class appears comparable within itself. Stations on small islands ought to be utterly rejected in tracing the effects of short period changes of solar radiation on terrestrial temperatures, and coast stations, as a rule, are little better. Inland stations are generally favorable. The average range of temperature for favorable stations is about 30 per cent of the range for the hypothetical stations, and as the fractional range of temperature for these latter is one-fourth the fractional change of insolation which produces it we conclude that for any given cycle of change of the "solar constant" having a period of several months the average fractional range of temperature, which would be found by a statistical comparison of actual with normal temperatures for a large number of selected inland stations, would not exceed 7.5 per cent of the range of the solar radiation which produced it. Owing, however, to the disturbing effects of local causes, the actual mean range found by combining a large number of good stations would be likely to be somewhat less than this maximum value. To produce an average temperature range of 1° C. for such selected stations, there would be required a fluctuation of solar radiation having a range of not less than 4.8 per cent if the period of the solar fluctuation did not exceed six months. For shorter solar periods larger changes of radiation will be required to produce equal temperature effects. For coast and island stations the effects upon individual stations will be reduced in the proportion of 2 and 4 to 1, respectively, on the average, as compared with selected inland stations; but owing to differential lag these effects may be utterly lost in combining the temperature differences at numerous coast and island stations.

In further illustration of the different behavior of inland and coast stations toward variations of solar radiation, Plate XXIV shows the average yearly march of temperature for three groups of stations of the United States, each group containing 12 stations and distributed in latitude from 32° to 48°, but having for each group the average latitude of about 39°.

Curve B is for Pacific coast stations—mean elevation 89 feet, mean latitude 40°.8; Curve D, Rocky Mountain stations—mean elevation 5,553 feet, mean latitude 39°.9; Curve C, stations of the plains—mean elevation 676 feet, mean latitude 38°.0; Curve E, for the "hypothetical earth" at latitude 39°.6; Curve A, the average intensity of solar radiation in calories per square centimeter per minute at latitude 39°.6.

As regards the temperature changes which might be expected to attend fluctuations of 5 per cent or more in solar radiation, having their complete cycle in six months' time or less, it appears from the comparison of temperatures and insolation between latitudes 10° N. and 5° S., where two maxima should occur yearly, as given in Table 40, that there is little likelihood of the recognition of solar cycles of six months or less in period and from 5 to 10 per cent in amplitude. But there are hardly any favorable inland meteorological stations in this zone, so that fully satisfactory evidence can not be collected. Of the four land stations—San Jose, Lado, Quito, and Kwai—in this zone the temperature of none follows the insolation in a close enough degree to show two clearly marked minima at the proper times; but San Jose and Kwai are both almost at the limit of the zone where a double minimum could be expected.

It may be objected by some that the investigation of the annual change of temperature as compared with the annual change of insolation which produces it is not a fair indication of the change of temperature to be expected as a consequence of a change in the "solar constant," for the reason that a flow of heat takes place from equatorial to polar regions which tends to reduce the change of temperature which is caused by the annual march of the sun's declination. But it must be recalled that this flow of heat constantly has the same general direction, namely, from the equator to the poles, in summer as well as in winter, and depends upon the fact that the temperature of the Tropics at all times exceeds the temperature of the polar regions. This difference of temperature is about 20° at minimum and 60° at maximum, so that for any given locality it is only the difference between the amounts of heat coming in and departing under the influence of a temperature gradient of 40° in 5,000 miles, which would be available to modify the annual march of temperatures which the change of insolation in that locality tends to produce.



TEMPERATURE AND INSOLATION, UNITED STATES.

Only an extensive investigation can determine the relative magnitudes of the effects of these two influences; but it seems almost certain that the effect of the temperature gradient is very small compared with that of change of insolation. The true major cause why the actual temperature fluctuation is less than that computed for the "hypothetical earth" is that the real earth has an enormous capacity for heat, more especially in the oceans, and therefore small islands and oceanic stations in general are little changed in their temperature, and only in a desert inland station like Timbuctu do we find effects approaching in magnitude those on the "hypothetical earth." This major cause is as operative against fluctuations of the "solar constant" as against annual changes of insolation, and therefore the comparison we have made seems a fair one.

COMPARISON OF OBSERVED WITH NORMAL TEMPERATURES.

The same local causes that unite to make the annual fluctuation of temperature at many oceanic stations small also unite to make the fluctuations from day to day or week to week small, and therefore many investigators have chosen oceanic stations for statistical temperature comparisons, in order to avoid the large irregular changes which are found in the records of inland stations. This procedure is not perhaps so objectionable when it is the eleven-year sun-spot cycle, or solar cycles of still longer period whose possible temperature effects principally interest them, but the results of statistical comparisons of oceanic stations are nearly worthless, or perhaps even quite misleading, as evidence regarding the existence of the short period fluctuations of solar radiation we are here discussing. Although the continents of the northern hemisphere furnish a large number of meteorological stations suitable for a statistical comparison of inland temperatures, Southern and Eastern Asia, Australia, Africa, and South America can not yet be adequately represented for lack of normal temperatures resulting from good records of many years' standing.

Nevertheless, it has seemed to us worth while to make an extensive statistical comparison of the temperatures of inland stations of the world for the purpose of obtaining evidence as to the reasonableness of a belief in solar fluctuations of a year or less in period. Great aid has been furnished by Mr. H. H. Kimball, librarian of the Weather Bureau, who has given valuable advice in the selection of stations, and has placed the library under his charge at our service for the purpose. The stations have been chosen to avoid large bodies of water, but otherwise to cover the earth with some degree of uniformity. A few stations are included of which the study of their lag in following the yearly changes of insolation would perhaps have dictated the exclusion; but where the data are so meager the choice can not be too particular. For many stations the departure of the monthly mean of maximum temperatures from its average value for the given month for many years has been the function employed. This function was used for two reasons: First, it is independent of the changes which have been made in the times of observation; second, as compared with the minimum temperature it is more directly influenced by solar radiation. It is possible that it would have been wiser to have employed departures from the mean of maxima and minima. For the European and Siberian temperature statistics, which were reduced before the difficulty of obtaining normals was encountered, the "mean" monthly temperatures have been generally employed. These have been carefully worked out under the care of such masters as Hann, Wild, and others, and are doubtless freed from defects introduced by changes of hours of observing. The computations involved in our comparison have been made chiefly by J. C. Dwyer of this Observatory.

As these temperature statistics are not a main feature of the work of this Observatory, it has not been deemed justifiable to print the departures and reductions complete, and only the general results and the method of reaching them will be stated.

The stations are 47 in number, and are distributed as follows: North America, 15; South America, 1; Europe, 8; northern Africa, 2; southern Africa, 2; northern Asia, 7; southern Asia, 6; Australia, 6.[1] The departures for each of these eight groups, excepting South America, were averaged separately with regard for sign. From the mean departures thus formed were found the deviations of the departures (excepting in the cases of northern and southern Africa) and thereby the "probable errors" of the several mean departures. From the average of the "probable errors" for Australia there was derived the average "probable error" of the departure of a single station, and this was regarded as the "probable error" of all the departures for the single South American station, which is thereafter treated as if it were a mean value. The "probable error" for northern Africa was similarly computed from the average "probable error" for southern Asia, and that for southern Africa from the average for Australia.

The eight several mean values of the departures for each month are assigned weights proportional inversely to the square of their "probable errors" (the "probable error" for each month is used, and not a mean of all), and directly to the

[1]In North America: Albany, Atlanta, Shreveport, Pittsburg, Bismarck, La Crosse, St. Louis, Yankton, Helena, Cheyenne, Dodge, El Paso, Yuma, Carson, Salt Lake. For these stations the normal temperatures given by Henry in Climatology of the United States were used.

In Europe: Vienna, Warsaw, Moscow, Kasan, Lugan, Tiflis, Elisabethgrad, Ekaterinburg. For these stations the normal temperatures used are those given by Wild and Hann.

In northern Asia: Barnaul, Irgis, Irkutsk, Kisil Avat, Nertchinsk, Peking, Tashkent. Normal temperatures as given by Wild or computed in one or two instances from the records actually used when Wild's series is too short.

In southern Asia: Nagpur, Bellary, Sibsagar, Benares, Lahore, Dera Ismail Kahn. Normal temperatures from the publications of the Indian meteorological service.

In Australia: Bourke, Deniliquin, Daly Waters, Alice Springs, Clare, York. Normals computed from the records reduced.

In northern Africa: Laghouat, Abbassia. Normal temperatures as published with records.

In southern Africa: Bloemfontein, Graaf Reinet. Normals computed from records used.

In South America: Cordoba. Normal temperatures as published by Davis.

area which they may fairly be supposed to represent. The factors of the weights depending on areas are as follows: North America, 12; South America, 2; Europe, 10; northern Asia, 20; southern Asia, 6; Australia, 8; northern and southern Africa, each 3. A weighted mean is thus found which represents fully one-third of the land area of the world.

The following Table 41 includes the preliminary mean departures of the separate groups, the weighted general mean, the "probable error" of the latter, the ratio between the general mean departure and its "probable error," and the number of cases of positive and negative departures among the means of the several groups.

TABLE 41.—*Monthly mean temperature departures of inland stations.*

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1875.													
January	−5.5			+0.5				+0.4	2	1	−2.56	1.44	1.8
February	−3.6			+0.3				+1.6	2	1	−0.71	0.89	0.8
March	−2.5			+2.4				−1.3	1	2	−1.58	0.61	2.6
April	−3.1			+2.3				+0.2	2	1	−2.48	1.01	2.5
May	+0.8			+1.3				+1.3	3	0	+0.96	0.11	8.7
June	0.0			+0.3	+0.3			−3.1	2½	1½	+0.02	0.24	0.1
July	−1.0			+1.0	+0.3			+0.2	3	1	−0.22	0.28	0.8
August	−1.2			+0.3	+0.1			0.0	2½	1½	−0.57	0.26	2.2
September	−1.3			−0.4	+0.5			+0.6	2	2	−0.78	0.28	2.8
October	+0.4			−1.0	+1.0			0.0	2½	1½	−0.05	0.33	0.2
November	−1.6			−0.2				−0.1	0	3	−0.57	0.30	1.9
December	+3.2			+0.1				−0.1	2	1	+1.22	0.95	1.3
1876.													
January	+3.8	−1.5	−1.0	+0.2				−1.4	2	3	+0.46	0.67	0.7
February	+3.0	+0.9	+0.4	+0.8	−1.4			−0.5	4	2	+0.88	0.24	3.7
March	−2.8	+2.5	+0.3	−0.8	+2.4			+0.5	4	2	+0.27	0.30	0.9
April	−0.6	+2.8	+1.1	+0.2	−1.4			+0.1	4	2	−0.63	0.62	1.0
May	+0.2	−2.0	+0.2	+0.4	−1.2			+1.4	4	2	−0.16	0.23	0.7
June	−0.1	+1.9	+0.8	+0.8				+0.1	5	0	+1.15	0.29	4.0
July	+0.7	+0.5	+0.9	−0.3				+1.2	4	1	+0.59	0.10	5.9
August	+0.4	+0.5	+0.3	+0.6	−1.4			−1.4	4	2	+0.32	0.11	2.9
September	−2.0	+1.6	−1.1	−0.2	−0.1			+1.7	2	4	−0.72	0.33	2.2
October	−1.5	−1.0	+1.8	−1.4				−0.3	1	4	−0.14	0.49	0.3
November	−1.4	−1.7	−1.8	−0.3	−2.1			−2.6	0	6	−1.60	0.16	10.0
December	−4.6	−1.2	−2.2	+0.6	+0.9			−1.4	2	4	−0.30	0.57	0.5
1877.													
January	−0.9	+1.2	−1.2	−0.7				+1.4	2	3	−0.32	0.34	0.9
February	+4.3	−0.6	−1.4	−1.8	+2.8			−0.5	2	4	−0.29	0.64	0.5−
March	−0.3	+1.8	+2.9	−0.8	−1.2			+2.4	3	3	+0.11	0.44	0.2
April	−1.6	−0.4	+0.8	−2.7	+0.3			+0.8	3	3	−0.66	0.31	2.1
May	−0.5	−0.4	+0.9	−1.9	−0.6			−1.6	1	5	−0.31	0.18	1.7
June	−0.9	+0.2	+0.9	+0.6	−1.1			+0.3	4	2	−0.23	0.21	1.1
July	0.0	+1.1	+0.7	+1.9	+0.9			+1.0	5½	½	+0.57	0.16	3.6
August	+0.3	+0.2	+0.8	+2.6	+1.9			−0.9	5	1	+0.71	0.19	3.7
September	+0.3	−1.1	+1.9	+1.6	−1.8			+0.2	4	2	−0.22	0.40	0.5+
October	−1.7	−0.7	+0.6	−0.6	−2.8			+2.4	2	4	−0.37	0.29	1.3
November	−1.3	+2.5	−0.4	+0.5	+0.5			+0.7	4	2	−0.04	0.39	0.1
December	+3.7	−0.8	−5.9	−0.7	+0.7			−0.6	2	4	−0.20	0.70	0.3

TABLE 41.—*Monthly mean temperature departures of inland stations*—Continued.

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1878.													
January	+2.1	−0.5	−2.4	−0.6	+3.9	−0.8	....	−1.7	2	5	−0.33	0.38	0.9
February	+4.0	+2.8	+1.5	+0.4	+0.7	−2.3	....	−0.7	5	2	+1.74	0.50	3.5
March	+5.3	+1.9	+4.5	+0.9	+0.6	0.0	....	+0.4	6½	½	+1.79	0.46	3.9
April	+1.2	+0.9	+0.9	−1.2	+0.6	+2.4	−0.9	−0.1	5	3	+1.05	0.13	8.1
May	−1.5	+0.2	+1.3	−1.9	−0.2	....	−0.7	−0.7	2	5	−0.10	0.29	0.3
June	−0.9	+1.6	+1.4	+1.7	−2.3	....	−2.6	−0.3	3	4	+0.06	0.42	0.1
July	+0.8	−1.1	+2.3	+0.3	+0.3	....	−3.3	−0.5	4	3	+1.10	0.36	3.1
August	+0.9	−0.7	+1.4	−0.6	+0.6	....	−4.9	−0.8	3	4	+0.35	0.29	1.2
September	−0.7	+1.2	+0.8	+0.4	+0.9	....	−2.3	+0.2	5	2	+0.69	0.15	4.6
October	−0.8	+2.4	−0.6	+0.8	+1.3	....	−1.8	+0.1	4	3	+0.12	0.35	0.3
November	+1.5	+3.2	−0.4	+0.9	−0.3	....	−1.6	+1.3	4	3	+0.74	0.23	3.2
December	−3.2	+3.3	−1.6	+0.9	−0.2	....	....	−0.6	2	4	−0.12	0.47	0.3
1879.													
January	−0.4	+0.2	−1.1	+1.8	+2.0	....	−2.3	−0.6	3	4	+0.32	0.34	0.9
February	+0.7	+3.0	+0.7	+1.9	−0.2	....	−1.3	+0.2	5	2	+1.21	0.36	3.4
March	+3.2	−0.1	+1.2	0.0	−0.4	....	+2.5	−0.6	3½	3½	+0.97	0.41	2.4
April	+0.3	+0.8	−0.8	+2.3	0.0	....	−3.3	−0.4	3½	3½	+0.57	0.34	1.4
May	+1.2	+0.7	+1.4	+0.6	−3.0	....	−1.5	−0.4	4	3	−0.57	0.55	1.0
June	+5.5	+0.1	+1.5	−1.1	−0.2	....	−2.7	−0.1	3	4	+1.38	0.44	3.1
July	+0.8	−0.5	+1.4	+0.4	−2.2	+0.9	−3.2	+0.5	5	3	+0.88	0.21	4.2
August	−0.2	−0.8	+0.3	−0.8	−0.7	+0.7	−2.8	−0.1	2	6	−0.50	0.14	3.6
September	−0.8	0.0	0.0	−0.3	−4.2	+0.3	−2.7	−0.2	2	6	−0.26	0.14	1.9
October	+2.2	+0.9	+0.3	−0.3	−2.3	+0.5	−2.3	−0.5	4	4	+0.65	0.37	1.7
November	+0.3	−0.8	+0.3	−0.7	−2.5	+0.6	−0.7	+0.9	4	4	−0.15	0.17	0.9
December	−0.1	−3.4	+2.0	−0.3	−0.3	−1.5	+0.2	+0.9	3	5	+0.85	0.38	2.2
1880.													
January	+5.4	−2.2	−2.4	+1.6	+1.1	−2.3	−1.7	+0.5	4	4	−0.46	0.63	0.7
February	+1.8	−1.2	−1.3	−0.4	+0.3	0.0	−1.8	−0.3	2½	5½	−0.37	0.25	1.5
March	−0.4	−1.5	+1.9	+3.0	−0.6	−1.5	−2.9	0.0	2½	5½	−0.07	0.37	0.2
April	0.0	−0.3	−1.0	+2.0	−0.6	+1.3	−3.3	−0.3	2½	5½	−0.32	0.27	1.2
May	+2.1	+0.5	+0.6	+0.8	+0.5	+0.4	−1.6	+0.4	7	1	+0.65	0.10	6.5
June	+0.9	−0.1	+0.5	+0.1	−0.6	+0.3	−3.1	+2.2	5	3	+0.13	0.13	1.0
July	−0.4	+1.0	+0.4	−0.7	+0.2	+0.6	−1.8	+0.1	5	3	+0.14	0.18	0.8
August	−0.1	+0.1	+0.3	+0.4	+2.4	−0.1	−2.1	+1.5	5	3	+0.22	0.12	1.8
September	−0.9	+0.3	+0.7	+0.3	−0.4	0.0	+0.7	−2.7	4½	3½	−0.25	0.17	1.5
October	−1.1	−0.6	+0.8	+0.6	−1.5	+1.2	−0.4	−1.3	3	5	−0.67	0.20	3.3
November	−5.2	+1.7	+2.5	−0.4	−0.7	+0.4	−1.6	+0.5	4	4	+0.01	0.51	0.0
December	−3.1	+2.7	+1.3	−0.4	+0.3	−0.8	−0.3	+0.9	4	4	−0.03	0.35	0.1
1881.													
January	−2.9	−1.1	+4.8	+1.1	−0.5	+4.2	−1.4	−1.8	3	5	−0.38	0.63	0.6
February	0.0	+0.8	−0.5	+1.6	+0.4	+0.5	−1.7	+0.7	5½	2½	+0.38	0.17	2.2
March	−0.7	+0.5	+1.5	−1.4	−0.6	....	−2.5	−0.1	2	4	−0.04	0.33	0.1
April	−0.7	+0.5	+1.9	−0.4	+0.6	+1.8	−2.7	+0.1	5	3	+0.27	0.30	0.9
May	+2.2	+0.8	0.0	+0.5	+0.9	−2.2	−0.4	+0.2	5½	2½	+0.33	0.16	2.0
June	+1.6	−0.7	−1.0	−0.5	−1.3	−0.2	0.0	−0.9	1½	6½	−0.79	0.17	5.2
July	+0.7	+0.6	+0.2	0.0	0.0	+0.3	−0.5	−2.0	5	3	+0.33	0.09	3.7
August	+1.5	−0.1	+0.3	−0.1	−0.2	+0.7	−0.9	−0.6	3	5	+0.25	0.10	2.5
September	+0.4	−1.7	−0.3	+0.4	−0.2	+1.2	+0.4	+1.2	5	3	+0.23	0.22	1.0
October	−0.1	−2.1	+0.4	+0.8	−1.0	0.0	+2.1	+0.4	4½	3½	+0.19	0.21	0.9
November	−1.2	−0.2	−0.9	+0.2	−1.4	−0.8	−0.9	+0.5	2	6	−0.24	0.15	1.6
December	+2.9	0.0	+1.6	+1.2	−0.3	−1.9	+1.3	+1.5	5½	2½	+0.78	0.29	2.7

TABLE 41.—*Monthly mean temperature departures of inland stations*—Continued.

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1882.													
January	+1.1	+4.1	+2.4	+1.3	+0.4	−2.6	+1.5	+0.6	7	1	+1.19	0.27	4.3
February	+3.4	+1.8	+1.0	+0.4	−0.2	−3.6	+0.7	+0.2	6	2	+0.63	0.36	1.7
March	+1.8	+1.9	+0.9	+1.6	+0.8	−2.9	+0.4	−0.4	6	2	+1.14	0.28	4.1
April	−0.4	+0.2	−0.5	+0.2	−0.9	−0.6	+0.9	−0.5	3	5	−0.13	0.11	1.2
May	−1.8	+1.3	+0.7	+0.1	−0.5	−0.8	−1.3	+0.8	4	4	+0.01	0.27	0.0
June	+0.3	0.0	+0.1	−0.2	−1.7	−1.0	+3.0	+0.1	4½	3½	+0.07	0.13	0.5
July	−0.8	+1.8	−0.3	−0.8	−0.7	−0.2	−0.2	−0.8	1	7	−0.24	0.20	1.2
August	+0.3	+0.5	+0.6	0.0	−0.3	+0.1	+0.4	+0.5	6½	1½	+0.40	0.08	5.0
September	0.0	0.0	+0.1	−0.6	+1.0	+0.1	−0.2	+0.8	5	3	+0.12	0.09	1.3
October	+0.1	−2.5	−2.2	0.0	+0.2	....	−1.9	+3.0	3½	3½	−0.89	0.38	2.3
November	−0.7	+1.6	−0.1	−0.5	+0.8	+0.1	−0.1	+0.3	4	4	−0.21	0.19	1.1
December	−0.4	−0.6	−3.9	+0.9	+0.5	....	−0.6	−0.9	2	5	−0.40	0.30	1.3
1883.													
January	−2.3	−2.1	−0.4	−0.2	+0.2	+0.2	−1.4	+0.8	3	5	−0.54	0.22	2.5
February	−0.9	+0.4	−2.6	−0.2	−0.8	−1.2	+1.9	+0.4	3	5	−0.60	0.23	2.2
March	−0.1	−1.4	+1.6	−0.4	−0.9	−1.5	−1.5	+1.4	2	6	−0.56	0.14	4.0
April	−0.7	−1.1	−1.1	+0.9	+0.1	−2.2	+0.8	−0.6	3	5	+0.23	0.22	1.0
May	−1.1	+1.5	−0.1	+0.4	−0.1	−1.0	+1.2	+0.4	4	4	−0.20	0.22	0.9
June	+0.8	+0.8	+0.3	+0.3	+1.6	+0.4	+0.9	+1.3	8	0	+0.67	0.07	9.6
July	−0.2	+0.8	−0.2	+0.6	+0.9	−0.2	+1.3	−0.1	4	4	+0,14	0.12	1.2
August	−0.4	−0.4	+0.2	+1.8	+0.3	−1.6	−3.6	−0.3	3	5	−0.19	0.21	0.9
September	−0.5	+0.8	−1.2	−0.1	−1.1	−0.1	+1.8	−0.2	2	6	−0.19	0.21	0.9
October	−2.8	+0.9	+1.3	−0.4	−0.8	−0.8	−0.2	+0.1	3	5	+0.20	0.27	0.7
November	+1.2	+1.6	−2.1	−1.1	−0.6	−0.4	+1.3	+0.1	4	4	+0.16	0.32	0.5
December	+0.1	+2.2	+1.8	−0.9	+0.2	−0.9	+0.8	0.0	5½	2½	+0.36	0.28	1.3
1884.													
January	−1.4	+1.1	+2.9	+0.1	+0.5	....	+0.2	+2.1	6	1	+0.58	0.54	1.1
February	−0.3	+2.1	+1.3	−0.4	+2.6	....	−0.9	+0.5	4	3	+0.73	0.34	2.1
March	−0.4	−1.0	−3.7	+0.5	+1.4	−0.7	−1.2	+0.8	3	5	−0.42	0.34	1.2
April	−1.8	−1.8	−1.1	−0.1	+0.4	+1.0	+0.2	−0.5	3	5	−0.26	0.24	1.1
May	0.0	−0.8	0.0	+0.3	−0.6	−1.0	−0.2	−1.8	2	6	−0.14	0.11	1.3
June	+0.9	−0.8	−0.1	0.0	+1.2	....	−0.8	−1.4	2½	4½	+0.11	0.20	0.5+
July	−0.4	+0.1	−0.7	0.0	0.0	−2.2	−2.4	−0.1	2	6	−0.42	0.12	3.5
August	−0.7	−1.5	−1.5	−0.1	+1.7	−1.2	+1.7	+3.8	3	5	−0.67	0.38	1.7
September	+0.4	−1.6	−1.1	−0.4	+0.9	−1.3	−1.2	+0.3	3	5	−0.19	0.25	0.8
October	+1.1	+0.8	−0.4	−1.2	−0.3	−1.3	−2.8	+0.3	3	5	+0.00	0.26	0.0
November	+0.9	0.0	−0.9	−1.1	−0.6	−0.9	−1.4	−0.3	1½	6½	−0.19	0.22	0.9
December	−3.1	+4.4	+1.6	−0.6	−1.7	−0.6	+1.4	+0.3	4	4	+0.32	0.56	0.6
1885.													
January	−2.3	−1.2	−1.1	−0.6	0.0	−0.5	+1.1	+1.1	2½	5½	−0.53	0.19	2.8
February	−1.6	+2.2	−0.6	−1.0	−0.5	+2.3	−1.4	−1.1	2	6	−0.34	0.34	1.0
March	0.0	+0.4	+0.6	+0.6	−2.1	+0.4	−0.7	−1.0	4½	3½	+0.37	0.16	2.3
April	+0.2	+0.3	−0.5	−1.4	−0.3	−1.8	−1.7	−1.0	2	6	−0.27	0.09	3.0
May	−0.4	+0.2	+0.1	−3.1	+1.8	−0.1	−1.7	−1.5	3	5	−0.37	0.20	1.8
June	−2.1	+1.0	+0.4	−0.5	−0.8	−1.4	+0.4	−0.9	3	5	−0.21	0.20	1.0
July	+0.5	+1.7	−0.3	+0.3	+1.4	−1.2	+1.5	−2.2	5	3	+0.27	0.22	1.2
August	−1.2	−1.9	+0.3	+0.3	+1.7	−0.2	+0.1	−0.4	4	4	−0.68	0.31	2.2
September	−0.3	−0.4	+0.6	+0.1	+0.9	−1.6	−1.6	+0.9	4	4	+0.44	0.10	4.4
October	−1.6	+0.8	+0.8	+0.3	+2.8	−1.7	−0.6	+0.5	5	3	+0.73	0.12	6.1
November	+1.1	−1.1	0.0	+0.3	+0.1	0.0	+0.7	+1.9	6	2	+0.60	0.17	3.5
December	+1.7	+1.9	+1.8	−1.1	+1.0	+1.1	+0.7	−0.1	6	2	+1.12	0.26	4.3

TABLE 41.—*Monthly mean temperature departures of inland stations*—Continued.

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1886.													
January	−3.0	+2.5	+1.8	−1.0	+1.4	+0.2	−0.2	+1.1	5	3	−0.18	0.41	0.4
February	+2.6	−2.2	−5.2	−0.6	0.0	+0.4	+1.8	+0.2	4½	3½	−1.16	0.45	2.6
March	−0.7	−1.2	−0.6	−1.0	+1.8	+1.1	−0.6	+0.4	3	5	−0.53	0.17	3.1
April	+0.4	+0.8	−0.7	+0.4	+1.5	−0.9	−0.5	0.0	4½	3½	+0.32	0.12	2.7
May	+2.6	+0.4	−0.2	−0.3	+1.4	−0.9	+1.3	+0.5	5	3	+0.69	0.28	2.5
June	+0.4	−0.9	−0.3	−0.6	+0.8	+0.1	+2.0	−0.9	4	4	−0.18	0.15	1.2
July	+1.5	−0.6	+0.2	−0.9	+1.8	−0.7	−3.3	+0.3	4	4	+0.13	0.25	0.5
August	+0.9	−0.1	0.0	+0.1	−0.4	−1.2	−1.0	+0.1	3½	4½	−0.01	0.10	0.1
September	0.0	0.0	+1.0	+1.1	+1.6	−1.4	+0.6	−0.6	5	3	+0.12	0.28	0.4
October	+0.5	−1.0	−2.0	−0.4	−1.4	−0.6	+0.1	+0.1	3	5	−0.32	0.30	1.1
November	−0.9	+1.5	−0.5	+0.1	+0.4	−1.3	−0.1	0.0	3½	4½	−0.14	0.13	1.1
December	−1.0	+5.4	+1.6	0.0	−1.9	+1.0	−3.1	+1.7	4½	3½	+0.58	0.34	1.7
1887.													
January	+0.1	+0.8	−3.5	−1.1	+2.1	+0.2	−0.4	+0.6	5	3	−2.16	0.46	4.7
February	−0.2	+0.7	+2.3	+0.7	−1.2	−1.2	+0.8	0.0	4½	3½	−0.13	0.29	0.4
March	+2.1	−0.4	+1.6	+0.9	−0.3	+1.4	−1.3	+0.9	5	3	+0.09	0.28	0.3
April	+0.5	0.0	+0.8	+0.7	−0.7	−0.1	−1.8	+0.1	4½	3½	+0.28	0.13	2.2
May	+2.5	+1.4	+0.3	+1.3	−0.7	+0.9	−1.1	0.0	5½	2½	+0.75	0.25	3.0
June	+1.5	−0.5	0.0	−1.3	−0.4	+0.4	+0.5	+3.0	4½	3½	−0.56	0.27	2.1
July	+0.8	+0.5	+0.8	−0.4	+0.6	−0.1	−0.5	+0.6	5	3	+0.58	0.09	6.4
August	−0.5	−0.4	−1.0	−0.9	0.0	+0.1	−2.0	+3.6	2½	5½	−0.55	0.12	4.6
September	−0.1	+2.0	+0.4	−0.2	−0.2	−0.2	+1.4	+0.8	4	4	+0.18	0.18	1.0
October	−1.1	−0.9	+1.9	−0.6	+0.2	+0.7	0.0	+0.4	4½	3½	−0.36	0.25	1.4
November	+1.5	+1.5	+3.3	−0.3	−0.7	+1.5	−1.1	−0.5	4	4	+0.96	0.29	3.3
December	−1.6	+2.5	+2.8	−0.1	−1.3	+0.6	−0.9	−0.6	3	5	−0.69	0.51	1.4
1888.													
January	−2.7	−0.7	+3.1	−1.4	+0.5	+0.3	−1.6	+3.1	4	4	−0.76	0.33	2.3
February	+2.0	−1.7	−2.0	−0.3	+0.6	−0.5	0.0	+1.0	3½	4½	−0.00	0.27	0.0
March	−2.0	−1.3	−1.0	+1.4	+0.3	+2.0	−1.6	+0.1	4	4	−0.83	0.34	2.4
April	+1.6	+2.1	+0.8	+0.8	+3.1	+0.9	−1.1	+1.9	7	1	+1.57	0.26	6.0
May	−1.3	+0.9	+1.2	0.0	+0.5	−0.4	−1.9	−0.5	3½	4½	+0.05	0.24	0.2
June	+0.2	−0.5	+1.2	+0.1	+1.8	+0.3	0.0	−2.7	5½	2½	+0.36	0.19	1.9
July	+0.3	−0.2	+0.9	−0.1	+1.2	+2.0	−0.8	+2.8	5	3	+0.43	0.12	3.6
August	−0.2	−0.6	+0.7	0.0	+0.6	+0.1	+0.6	+1.6	5½	2½	+0.43	0.12	3.6
September	+0.3	+0.2	−0.2	+0.8	+1.5	+1.1	−2.3	+1.3	6	2	+0.23	0.18	1.3
October	−0.8	+0.7	+1.7	+1.1	+1.3	+1.0	+0.9	+0.3	7	1	+0.48	0.22	2.2
November	−0.4	−1.3	+1.1	−0.3	+3.1	+0.2	+0.6	+0.5	5	3	−0.01	0.20	0.0
December	+1.3	−2.1	−0.1	−0.1	+1.8	+0.7	+1.3	+1.2	5	3	+0.47	0.22	2.1
1889.													
January	+0.6	−2.5	−4.3	+1.2	+0.1	+0.3	+0.7	−0.9	5	3	−0.39	0.46	0.8
February	−0.8	+1.0	+3.1	−0.9	+1.9	+2.2	−0.1	−1.7	4	4	+0.69	0.39	1.8
March	+3.0	−2.4	+0.6	+0.7	+2.3	0.0	+1.7	0.0	6	2	+0.65	0.40	1.6
April	+2.0	+0.9	+0.2	+0.6	+0.7	+0.2	+2.6	−1.6	7	1	+0.86	0.14	6.1
May	+0.2	+2.6	−0.7	−0.3	0.0	+1.1	+2.6	−0.3	4½	3½	−0.29	0.20	1.4
June	+0.2	+0.3	+1.2	−0.4	+0.6	+1.2	+1.1	+0.1	7	1	+0.24	0.19	1.3
July	0.0	+0.5	+0.5	−0.1	+0.4	+1.5	+1.4	−0.7	5½	2½	+0.26	0.08	3.2
August	+0.7	−0.1	+0.4	−0.1	−0.2	+1.6	+1.7	−1.8	4	4	+0.27	0.12	2.2
September	−0.9	−1.1	−0.1	0.0	+0.8	+0.7	0.0	−0.7	3	5	−0.60	0.15	4.0
October	−0.4	+1.6	−2.1	−0.7	+1.0	+1.7	−1.2	+0.1	4	4	+0.18	0.29	0.6
November	−1.2	0.0	−2.7	0.0	+0.6	0.0	−1.0	−1.1	2½	5½	−0.69	0.23	3.0
December	+4.0	−1.0	−1.8	+0.9	+1.1	−1.1	−1.2	−1.1	3	5	+0.14	0.43	0.3

TABLE 41.—*Monthly mean temperatnre departures of inland stations*—Continued.

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1890.													
January	0.0	+1.3	+0.7	+0.8	+0.8	+0.3	−0.2	−1.0	5½	2½	+0.57	0.16	3.6
February	+1.4	+0.3	+0.1	+1.6	−0.2	+0.2	−1.9	−0.9	5	3	+0.44	0.22	2.0
March	−0.8	+3.1	−0.9	−0.3	0.0	−1.1	+0.4	−1.7	2½	5½	−0.18	0.24	0.7
April	+0.9	+1.8	−0.6	+0.1	−0.4	−0.2	−1.8	−2.4	3	5	+0.43	0.21	2.0
May	+0.1	+0.8	−0.2	+0.7	+0.6	+0.7	−1.5	−0.7	5	3	+0.24	0.12	2.0
June	+1.1	+0.1	+0.8	−1.5	+0.4	−0.3	+1.3	−0.9	5	3	+0.44	0.21	2.1
July	+0.7	+1.4	+0.1	−1.6	−0.3	+0.8	−0.7	+1.1	5	3	+0.33	0.19	1.7
August	−0.7	+1.6	−0.3	−1.3	−0.5	+1.4	+0.5	−1.4	3	5	−0.38	0.16	2.4
September	−5.5	+0.4	−0.6	−0.4	+0.2	−1.3	+1.7	−1.6	3	5	−1.68	0.65	2.6
October	−1.0	−0.2	+1.5	−0.7	+0.3	−1.4	−3.6	+0.3	3	5	−0.46	0.21	2.2
November	+1.8	−1.8	−1.0	−1.1	−1.0	−0.1	−2.4	+2.8	2	6	+0.42	0.37	1.1
December	+1.7	−2.2	−1.6	−1.2	−0.7	−0.4	−1.7	+0.8	2	6	−0.48	0.32	1.5
1891.													
January	+1.3	−3.1	−2.4	−1.3	−1.6	−0.4	−1.3	−1.0	1	7	−1.12	0.33	3.4
February	−0.7	0.0	+0.6	−1.8	+0.2	+1.4	−1.4	+0.4	4½	3½	+0.35	0.13	2.7
March	−2.7	+1.6	+1.7	−3.0	+1.3	+1.0	−0.1	+0.1	5	3	−0.71	0.52	1.4
April	+0.6	−0.4	−1.2	−0.7	−1.1	+1.3	−3.3	−0.1	2	6	−0.16	0.21	0.8
May	−0.4	+1.7	+0.3	−1.1	+0.9	+0.6	−0.5	−0.3	4	4	+0.24	0.22	1.1
June	−1.1	+0.5	−0.3	+1.8	−0.7	+0.6	−0.9	+1.2	4	4	−0.40	0.18	2.2
July	−1.7	+0.6	+0.4	+1.4	−0.3	+0.6	+0.2	−1.2	5	3	−0.20	0.23	0.9
August	−0.5	−0.2	+0.7	0.0	−0.7	+0.3	−1.1	0.0	3	5	−0.11	0.12	0.9
September	+1.0	−0.2	+0.2	+0.2	−0.3	+0.5	+0.2	−0.2	5	3	+0.21	0.12	1.8
October	+0.2	0.0	+0.1	−0.7	0.0	+0.9	+2.0	0.0	5½	2½	−0.01	0.10	0.1
November	−0.1	−2.7	−1.9	+0.5	+0.3	+0.9	+1.6	−0.6	4	4	+0.00	0.23	0.0
December	+1.3	+3.1	+0.5	+0.6	+0.4	+0.8	−1.5	−2.1	6	2	+0.77	0.20	3.8
1892.													
January	−1.1	−0.3	−0.1	+1.0	+0.6	+1.2	+2.6	−0.6	4	4	−0.23	0.24	1.0
February	+1.6	+2.0	−0.5	+1.3	+2.9	+1.5	+3.0	+1.2	7	1	+1.65	0.16	10.3
March	−0.7	−0.2	−3.7	+2.6	+2.1	+1.6	+1.4	−1.0	4	4	−0.43	0.40	1.1
April	−1.8	−0.2	−0.9	+3.1	−0.2	−0.6	+0.8	−0.1	2	6	−0.82	0.21	3.9
May	−2.6	+1.4	+0.4	+0.9	0.0	−0.6	+2.0	−1.1	4½	3½	+0.10	0.19	0.5
June	−0.3	+1.8	+0.4	−0.1	+0.3	+0.9	+2.2	−1.4	5	3	+0.32	0.13	2.5
July	−0.6	+0.1	0.0	−0.1	+0.7	+0.3	+2.5	+0.3	5½	2½	−0.16	0.10	1.6
August	+0.2	+0.7	0.0	−1.6	+1.4	+0.1	+1.8	−2.3	5½	2½	+0.14	0.12	1.2
September	+1.3	+1.4	−0.2	−0.9	−0.2	+1.3	+0.4	−0.9	4	4	+0.53	0.21	2.5
October	−0.1	0.0	+0.4	−0.3	−0.6	+0.2	−0.8	−0.3	2½	5½	+0.12	0.09	1.3
November	−0.3	−0.1	−2.9	−0.3	0.0	−0.4	+1.4	−0.4	1½	6½	−0.38	0.19	2.0
December	−2.4	−1.6	0.0	−0.6	−0.7	−0.1	+0.1	−0.4	1½	6½	−1.27	0.24	5.3
1893.													
January	−0.7	−6.2	−5.8	−2.4	+0.2	+0.2	+0.6	−0.6	3	5	−2.11	0.65	3.2
February	−1.3	0.0	−2.9	−3.5	+1.8	0.0	+2.2	−1.8	3	5	−0.48	0.48	1.0
March	−0.9	+1.5	+2.5	−3.2	+1.3	−0.5	+2.2	+0.4	5	3	−0.34	0.34	1.0
April	−1.4	−0.8	+2.7	−0.3	−0.2	−0.6	+0.5	−0.3	2	6	−0.13	0.40	0.3
May	−1.1	0.0	−0.3	−1.1	+0.8	+0.5	+0.4	−0.6	3½	4½	−0.10	0.21	0.5
June	+1.0	−0.2	+1.3	−2.4	−1.2	+0.4	+1.1	−1.6	4	4	+0.08	0.23	0.3
July	+0.4	+0.1	+0.4	−1.3	+1.1	+0.1	−0.1	+1.2	6	2	+0.30	0.10	3.0
August	−0.1	+0.1	−0.2	−0.3	0.0	−0.3	+0.7	−1.9	2½	5½	−0.04	0.05	0.8
September	+0.3	+0.2	+0.9	−1.3	+0.6	+1.6	−1.8	−2.7	5	3	−0.05	0.22	0.2
October	−0.1	+1.7	0.0	−0.8	+1.6	+1.4	−2.3	−2.1	3½	4½	+0.27	0.22	1.2
November	−0.4	+1.1	+1.6	−1.0	−0.6	+1.2	+0.2	−1.2	4	4	−0.31	0.13	2.4
December	+0.7	+1.5	+1.1	−0.5	+0.3	−0.7	−0.3	+1.0	5	3	+0.36	0.17	2.1

TABLE 41.—*Monthly mean temperature departures of inland stations*—Continued.

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1894.													
January	+0.4	−0.4	−0.7	−1.1	+0.6	+0.5	+0.2	+0.2	5	3	−0.11	0.16	0.7
February	−1.6	+2.9	+3.2	0.0	−1.7	−1.0	−0.6	+0.5	3½	4½	+0.32	0.50	0.6
March	+1.8	+1.0	+1.0	−1.1	−0.5	0.0	+1.5	−1.7	4½	3½	+0.71	0.14	5.1
April	+0.4	+0.1	−1.9	−0.2	−0.6	−0.8	−0.9	−0.5	2	6	−0.27	0.21	1.3
May	+0.7	+1.0	+0.8	+0.6	−1.1	+0.3	−0.3	+1.4	6	2	+0.64	0.11	5.8
June	+0.1	−1.6	+0.2	−1.1	+0.6	+0.3	+0.4	−0.7	5	3	−0.18	0.18	1.0
July	+0.7	−0.4	0.0	−1.5	−0.4	−0.2	+1.2	−0.3	2½	5½	−0.14	0.11	1.3
August	+0.3	+0.2	+0.3	−0.8	−0.5	−0.3	+2.2	−0.7	4	4	−0.06	0.14	0.4
September	−0.1	−2.2	+0.4	−0.8	−1.4	+1.4	0.0	−1.1	2½	5½	−0.56	0.21	2.7
October	+0.8	−0.5	+0.6	−0.6	−1.0	+2.4	+0.9	−1.3	4	4	+0.22	0.20	1.1
November	+1.3	+0.2	0.0	−1.2	+0.8	+0.2	+2.0	+0.7	6½	1½	+0.37	0.20	1.8
December	−0.2	+0.1	−1.7	−0.9	−1.1	+0.3	−0.3	0.0	2½	5½	−0.50	0.14	3.6
1895.													
January	−1.6	+1.9	−2.2	−0.7	−2.1	+0.3	+1.1	−1.9	3	5	−1.21	0.24	5.0
February	−2.8	−1.6	−0.7	+0.4	−0.6	+3.6	+0.8	+0.5	4	4	−0.51	0.46	1.1
March	+0.3	+0.9	+1.2	−0.7	+0.1	0.0	+1.3	+1.2	6½	1½	−0.06	0.17	0.4
April	+1.5	−0.5	+0.9	−1.0	0.0	+2.5	−0.9	+1.7	4½	3½	+0.68	0.20	3.4
May	+0.2	−0.3	−0.6	+1.3	−0.3	0.0	+1.1	+0.8	4½	3½	−0.21	0.12	1.8
June	−5.5	0.0	−0.4	−1.0	+0.4	−0.9	0.0	+3.3	3	5	−0.83	0.45	1.8
July	−1.6	+0.5	+0.4	0.0	−0.8	+0.4	+1.9	+2.0	5½	2½	+0.19	0.29	0.4
August	+0.2	0.0	−0.6	−0.6	+1.0	−0.6	+3.1	+1.5	4½	3½	−0.05	0.14	0.4
September	+1.5	+0.2	+0.5	+0.4	+0.6	−0.4	+0.5	+0.2	7	1	+0.70	0.13	5.4
October	−0.8	+1.8	+0.1	−0.4	+1.9	+1.9	+2.2	−0.4	5	3	+0.21	0.19	1.1
November	−0.7	+0.5	+0.8	+1.0	0.0	+2.3	+2.0	−1.0	5½	2½	+0.22	0.22	1.0
December	−0.3	−0.4	+1.0	0.0	+0.3	+1.5	−0.5	+0.7	4½	3½	+0.17	0.14	1.2
1896.													
January	+1.5	−2.5	+2.4	+0.8	+0.8	+0.4	+1.3	−0.4	6	2	+0.89	0.20	4.4
February	+2.1	−0.5	+0.5	+0.9	−0.3	+0.1	+2.3	−0.2	5	3	+0.32	0.24	1.3
March	−1.1	+0.2	−0.6	+0.7	+0.2	+0.5	+3.6	+0.5	6	2	−0.51	0.27	1.9
April	+0.7	−2.5	−1.3	+0.9	−0.4	−1.1	+2.1	+1.3	4	4	−1.11	0.22	5.0
May	+1.1	−0.1	+0.2	+1.2	−0.5	−1.5	+1.1	+1.9	5	3	+0.19	0.18	1.0
June	+1.1	+0.4	+0.7	−0.2	−0.3	−0.7	+0.5	−0.2	4	4	+0.49	0.14	3.5
July	−0.7	−0.2	0.0	+0.4	−1.2	....	+1.5	+3.5	3½	3½	−0.22	0.16	1.4
August	+5.5	0.0	+0.2	−0.1	−1.1	....	+0.5	+4.0	4½	2½	+1.15	0.64	1.8
September	−0.7	+0.2	0.0	+0.5	−0.7	....	+2.7	+2.5	4½	2½	−0.11	0.17	0.6
October	−0.5	+2.6	+0.2	+1.6	+2.7	−1.4	+3.6	+1.2	6	2	+0.92	0.38	2.4
November	−1.4	−1.8	+1.3	+0.7	+0.6	−1.3	+1.0	+0.5	5	3	−0.49	0.33	1.5
December	+2.1	−0.1	−0.7	+0.3	+0.5	0.0	+2.3	−0.3	4½	3½	+0.38	0.26	1.4
1897.													
January	−1.1	+0.3	+0.3	+0.6	−0.6	+0.5	−0.4	−0.7	4	4	−0.29	0.18	1.6
February	−0.1	+0.7	0.0	+1.1	0.0	+0.6	+2.6	+0.4	6	2	+0.36	0.16	2.4
March	−1.4	+0.8	−2.6	−0.1	−1.3	+1.0	+1.3	+2.4	4	4	−1.57	0.35	4.5
April	−0.3	+1.0	−0.3	−0.1	+2.5	−0.1	+4.4	+2.0	4	4	+0.72	0.33	2.2
May	+0.1	+2.5	−0.8	+0.8	+1.2	+0.5	+2.7	+1.0	7	1	+0.70	0.23	3.0
June	−0.4	+1.4	+0.5	0.0	+2.4	+0.2	+1.0	+0.7	6½	1½	+0.20	0.35	0.6
July	0.0	+0.5	+0.8	+0.8	+0.7	−0.6	+1.2	−1.9	5½	2½	+0.39	0.11	3.5
August	−0.3	+0.5	+0.7	−0.9	−0.2	−0.3	+1.9	−1.8	3	5	+0.17	0.14	1.2
September	+1.4	+0.7	+0.9	−0.6	+0.1	....	+0.6	−0.8	5	2	+0.26	0.13	2.0
October	+1.2	0.0	+1.4	+0.2	−0.6	....	+1.1	+1.3	5½	1½	+0.20	0.19	1.0
November	+0.7	−1.2	+3.1	+0.4	+1.6	....	+0.3	−0.2	5	2	+0.53	0.24	2.2
December	−1.3	−1.1	+1.2	−0.2	+0.6	....	+2.9	+0.9	4	3	−0.74	0.24	3.1

TABLE 41.—*Monthly mean temperature departures of inland stations*—Continued.

Year and month.	Average departure from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1898.													
January	+1.1	+1.5	+3.0	+1.0	+1.3	−1.9	−0.8	+0.6	6	2	+0.98	0.26	3.7
February	+2.7	+0.5	−1.2	−0.8	+0.4	−0.3	−1.2	+1.4	4	4	+0.06	0.35	0.2
March	+0.8	−2.9	−3.7	−0.4	−0.5	−0.9	+2.4	−1.1	2	6	−0.29	0.35	0.8
April	0.0	−1.2	−0.7	+0.9	−0.8	−0.9	+1.4	−1.0	2½	5½	−0.67	0.17	3.9
May	−0.9	+1.9	−1.0	−0.2	−1.4	−0.2	−0.4	+1.1	2	6	−0.44	0.24	1.8
June	+0.8	−0.1	+0.3	0.0	0.0	+0.3	+1.3	+2.4	6	2	+0.19	0.09	2.1
July	−0.2	+0.3	−0.1	−2.1	+0.6	0.0	+0.5	−1.5	3½	4½	−0.07	0.12	0.6
August	+0.6	+0.4	0.0	−0.2	+1.3	−0.5	+1.4	−2.1	4½	3½	+0.35	0.12	3.9
September	+1.1	+0.1	−0.8	−0.7	+0.3	−1.2	+0.9	−1.0	4	4	+0.15	0.22	0.7
October	−1.6	−1.7	+1.0	+0.2	+0.6	+1.3	−2.9	−2.0	4	4	+0.75	0.18	4.2
November	−1.3	+1.8	+1.6	+0.2	−1.2	+0.3	+0.8	−1.9	5	3	−0.80	0.23	3.5
December	−2.1	+4.1	+2.1	+0.3	+0.3	−0.8	+1.1	+0.1	6	2	+0.04	0.45	0.1
1899.													
January	+1.2	+5.4	+3.0	−0.8	−3.7	+1.0	+0.8	....	5	2	+1.16	0.43	2.7
February	−3.6	+2.6	+2.3	+0.5	+1.2	+0.9	+1.3	....	6	1	+0.77	0.45	1.7
March	−1.9	+0.2	+1.6	+1.2	−0.9	−1.0	−1.1	....	3	4	+0.82	0.30	2.7
April	−0.1	+1.3	+0.3	−0.9	+0.6	+0.5	−2.7	....	4	3	+0.37	0.23	1.6
May	−0.3	+0.4	+0.8	+0.3	−0.3	+0.5	−4.0	....	4	3	+0.35	0.18	2.0—
June	+0.3	−0.4	+1.0	−0.8	−0.3	−2.3	−1.4	....	2	5	+0.42	0.20	2.1
July	−0.1	+0.3	−0.4	−0.7	−0.6	−1.8	−2.8	....	1	6	−0.21	0.14	1.5
August	+0.2	−0.7	+0.7	+1.3	−1.2	−1.8	−0.7	....	3	4	−0.03	0.26	0.1
September	+0.9	+0.8	+0.3	+1.6	+0.8	+0.2	+0.8	....	7	0	+0.70	0.08	8.8
October	+0.2	+0.9	+1.0	+1.2	−1.1	−0.1	−1.5	....	4	3	−0.24	0.27	0.9
November	+2.9	+2.5	+2.1	+1.4	−0.6	−0.7	−1.3	....	4	3	+1.45	0.40	3.6
December	−0.5	−2.6	−2.7	+1.4	+0.6	−0.1	+0.5	....	3	4	−0.92	0.33	2.8
1900.													
January	+3.7	0.0	−5.0	+0.4	0.0	+0.1	....	....	4	2	+0.93	0.83	1.1
February	−0.1	+1.5	−0.5	+1.1	+2.4	+3.0	....	....	4	2	+0.72	0.31	2.3
March	+0.9	−0.1	+1.4	+1.6	−1.4	−0.1	....	....	3	3	+0.72	0.26	2.8
April	0.0	−0.7	−0.9	−0.9	+0.1	−1.3	+1.7	....	2½	4½	−0.56	0.14	4.0
May	+1.4	+0.1	−0.1	0.0	−0.1	−2.1	+2.3	....	3½	3½	+0.69	0.26	2.7
June	+1.6	−0.4	+0.7	+1.1	+0.2	−1.9	−1.1	....	4	3	+0.20	0.24	0.8
July	0.0	+0.4	+0.4	+0.1	−1.3	−1.9	+0.6	....	4½	2½	−0.28	0.20	1.4
August	+1.3	+0.2	+0.4	+0.1	−0.3	−1.4	−2.1	....	4	3	+0.19	0.17	1.1
September	+0.1	−0.6	+0.9	−1.1	−1.6	−1.1	+1.5	....	3	4	−0.47	0.26	1.8
October	+2.1	+1.6	+0.7	−0.6	+0.3	+0.3	−1.0	....	5	2	+0.62	0.24	2.6
November	+0.2	−0.1	−0.6	+1.2	+1.4	−1.6	+0.4	....	4	3	+0.61	0.23	2.7
December	+1.4	+2.9	+0.6	+0.2	+0.2	0.0	−2.4	....	5½	1½	+1.48	0.34	4.4
1901.													
January	+1.6	+0.5	+0.8	−1.3	−0.3	−0.4	0.0	....	3½	3½	+0.81	0.29	2.4
February	−1.2	+1.1	+1.5	−1.0	+0.5	−0.5	−1.8	....	3	4	−0.46	0.31	1.5
March	+0.6	+0.8	+1.9	−0.1	−1.2	+1.0	−2.3	....	4	3	+0.54	0.26	2.1
April	−0.6	+1.9	+1.1	−0.5	−0.2	+1.1	−0.3	....	3	4	+0.17	0.26	0.7
May	+0.7	+0.5	−0.1	−0.5	+1.1	−1.6	−0.4	....	3	4	+0.21	0.18	1.2
June	+0.4	+1.7	−1.0	+1.0	−1.1	+0.4	+0.3	....	5	2	−0.54	0.24	2.2
July	+2.3	+0.7	+0.5	+0.7	−1.7	−0.3	+0.1	....	5	2	+0.45	0.29	1.6
August	+1.1	+0.6	+0.3	−0.2	−0.9	−0.7	+1.2	....	4	3	+0.48	0.06	8.0
September	−0.9	−0.8	+0.4	−0.6	+0.8	−0.9	−2.6	....	2	5	−0.57	0.22	2.6
October	+1.1	0.0	−1.4	+1.4	−1.1	−2.4	−3.5	....	2½	4½	+0.37	0.33	1.1
November	+0.8	0.0	+2.7	+0.8	+1.6	−0.7	−2.3	....	4½	2½	+1.12	0.35	3.2
December	−1.4	+2.0	+0.7	+0.7	+1.4	−1.1	−0.3	....	4	3	+0.50	0.26	1.9

TABLE 41.—*Monthly mean temperature departures of inland stations*—Continued.

Year and month.	Average departures from normal monthly temperatures.								Number of departures.		General mean.	Probable error.	Ratio of general mean to probable error.
	North America.	Europe.	Northern Asia.	Southern Asia.	Australia.	Northern Africa.	Southern Africa.	South America.	Positive.	Negative.			
1902.													
January......	0.0	+3.8	+3.7	+1.8	−1.0	−0.2	−1.5	....	3½	3½	+0.64	0.40	1.6
February.....	−0.3	+2.2	+1.4	+1.2	+0.2	+1.5	+0.6	....	6	1	+1.18	0.23	5.1
March........	+0.3	+0.5	+1.0	+1.1	+1.1	+0.4	+0.1	....	7	0	+0.63	0.09	7.0
April.........	0.0	−0.9	−1.5	−0.2	+1.8	+0.7	−0.4	....	2½	4½	0.00	0.33	0.0
May..........	+0.9	−0.8	−0.8	+0.7	+1.9	−1.1	+2.2	....	4	3	+0.53	0.24	2.2
June..........	−0.3	+0.5	−0.3	+0.4	+0.4	−0.9	−0.4	....	3	4	+0.05	0.13	0.4
July..........	−1.2	−0.3	−0.6	+0.2	+1.2	−0.4	+2.0	....	3	4	−0.54	0.17	3.2
August.......	−0.3	0.0	−0.3	+1.0	0.0	−0.6	−1.3	....	2	5	−0.07	0.12	0.6
September....	−0.8	−1.2	+0.6	−0.2	+0.6	−0.7	−3.6	....	2	5	−0.33	0.19	1.7
October......	+1.0	−1.8	−0.2	0.0	+0.6	−0.9	−0.3	....	2½	4½	+0.04	0.31	0.1
November....	+1.2	−3.4	−0.4	+0.1	+1.4	−0.6	−0.9	....	3	4	−0.10	0.28	0.4
December.....	−1.6	−2.1	+1.0	−0.1	−2.3	−0.3	+1.1	....	2	5	−0.46	0.44	1.0
1903.													
January......	+1.3	+2.0	+2.1	+0.4	....	....	+1.9	....	5	0	+1.31	0.27	4.8
February.....	−1.8	+3.2	+5.3	+0.5	....	....	+0.4	....	4	1	+0.91	0.72	1.3
March........	+1.3	+1.9	−2.2	−0.7	....	....	+0.1	....	3	2	+0.53	0.47	1.1
April.........	−0.4	+2.6	−0.7	−0.7	....	....	−1.3	....	1	4	−0.36	0.23	1.6
May..........	−0.3	+0.7	−0.4	−1.1	....	....	−0.2	....	1	4	−0.07	0.20	0.3
June..........	−1.3	+1.3	+0.1	+1.2	....	....	−1.2	....	3	2	−0.33	0.35	0.9
July..........	−0.7	+0.3	+0.6	−0.2	....	....	−0.3	....	2	3	−0.19	0.16	1.2
August.......	−0.8	0.0	+0.1	−0.4	....	....	−0.4	....	1½	3½	−0.36	0.14	2.6
September....	−0.9	0.0	+0.1	−0.3	....	....	+1.3	....	2½	2½	−0.12	0.13	0.9
October......	+0.9	−0.1	−0.8	−0.4	....	....	−0.4	....	1	4	+0.26	0.23	1.1
November....	−0.2	+1.7	−0.3	−0.3	....	....	−0.7	....	1	4	−0.02	0.22	0.1
December.....	−0.7	+0.5	−1.5	0.0	....	....	+0.9	....	2½	2½	−0.26	0.26	1.0
1904.													
January......	−0.5	....	....	−0.6	....	....	−2.4	....	0	3	−0.68	0.20	3.4
February.....	0.0	....	....	+0.9	....	....	−1.7	....	1½	1½	+0.08	0.44	0.2
March........	+0.8	....	....	−1.6	....	....	−1.6	....	1	2	+0.07	0.52	0.1
April.........	−1.3	....	....	+0.3	....	....	+0.4	....	2	1	−0.39	0.39	1.0
May..........	+0.1	....	....	−0.3	....	....	−0.1	....	1	2	−0.07	0.10	0.7
June..........	−0.6	....	....	−0.2	....	....	−1.1	....	0	3	−0.52	0.11	4.7
July..........	−1.4	....	....	+0.1	....	....	+0.4	....	2	1	−1.19	0.25	4.8
August.......	−0.8	....	....	+0.2	....	....	−0.5	....	1	2	−0.56	0.20	2.8
September....	+0.1	....	....	+0.3	....	....	−1.8	....	2	1	+0.17	0.16	1.1
October......	0.0	....	....	+0.3	....	....	−1.4	....	1½	1½	+0.11	0.14	0.8
November....	+2.6	....	....	−0.3	....	....	+0.8	....	2	1	+0.92	0.66	1.4
December.....	−0.2	....	....	0.0	....	....	−1.8	....	1½	2½	−0.21	0.18	1.2
1905.													
January......	−1.6	....	....	−1.6	....	....	+0.9	....	1	2	−1.25	0.42	3.0
February.....	−3.1	....	....	−3.4	....	....	−0.7	....	0	3	−2.81	0.46	6.1
March........	+2.8	....	....	−3.0	....	....	−1.4	....	1	2	+1.04	1.18	0.9
April.........	−1.8	....	....	−1.9	....	....	0.0	....	½	2½	−1.69	0.23	7.3
May..........	−1.3	....	....	+0.5	....	....	+0.2	....	2	1	−0.63	0.41	1.5
June..........	−0.2	....	....	+1.6	....	....	−1.9	....	1	2	−0.12	0.30	0.4
July..........	−1.2	....	....	+0.4	....	....	....	....	1	1	−0.47	0.53	0.9
August.......	+0.4	....	....	+0.4	....	....	....	....	2	0	+0.40	0.00	....
September....	+0.8	....	....	−0.2	....	....	....	....	1	1	+0.50	0.31	....
October......	−1.6	....	....	+0.3	....	....	....	....	1	1	−0.85	0.65	1.3
November....	+0.7	....	....	+1.0	....	....	....	....	2	0	+0.88	0.09	9.8
December.....	−0.7	....	....	−0.2	....	....	....	....	0	2	−0.46	0.17	2.7

The principal object of the investigation of temperature departures just given is to aid us to decide if there occur simultaneously variations of temperature over the earth's surface which could most probably be ascribed to influences outside the earth, and which, if found, would be most reasonably ascribed to the variation of solar radiation.

As Table 41 includes values for about 300 successive months, there are a sufficient number of cases to fall properly under the laws of the probability of accidental variations, if the variations are really of local origin and independent of one another. In the following table is stated the number of cases in which the general mean departure as given in Table 41, lies between different multiples of the "probable error" and the number of cases which should be found if the departures for the separate groups were purely due to local causes, and therefore independent.

	Between—								
	0 and $\frac{1}{2}$ P E.	$\frac{1}{2}$ and $\frac{2}{2}$. P E.	$\frac{2}{2}$ and $\frac{3}{2}$. P E.	$\frac{3}{2}$ and $\frac{4}{2}$. P E.	$\frac{4}{2}$ and $\frac{5}{2}$. P E.	$\frac{5}{2}$ and $\frac{6}{2}$. P E.	$\frac{6}{2}$ and $\frac{7}{2}$. P E.	$\frac{7}{2}$ and $\frac{8}{2}$. P E.	$\frac{8}{2}$ and ∞. P E.
Observed......	47	56	71	39	42	24	20	23	38
Computed.....	95	85	68	49	31	18	9	4	3

So far as this comparison shows, the departures do not fall as dictated by the laws of probability of accidental variations. But it may be urged that the values of the probable error employed are more or less arbitrary, since they depend on the weights assigned to the different observations; for the judgment of different persons might well differ as to what weights to employ in so difficult a situation.

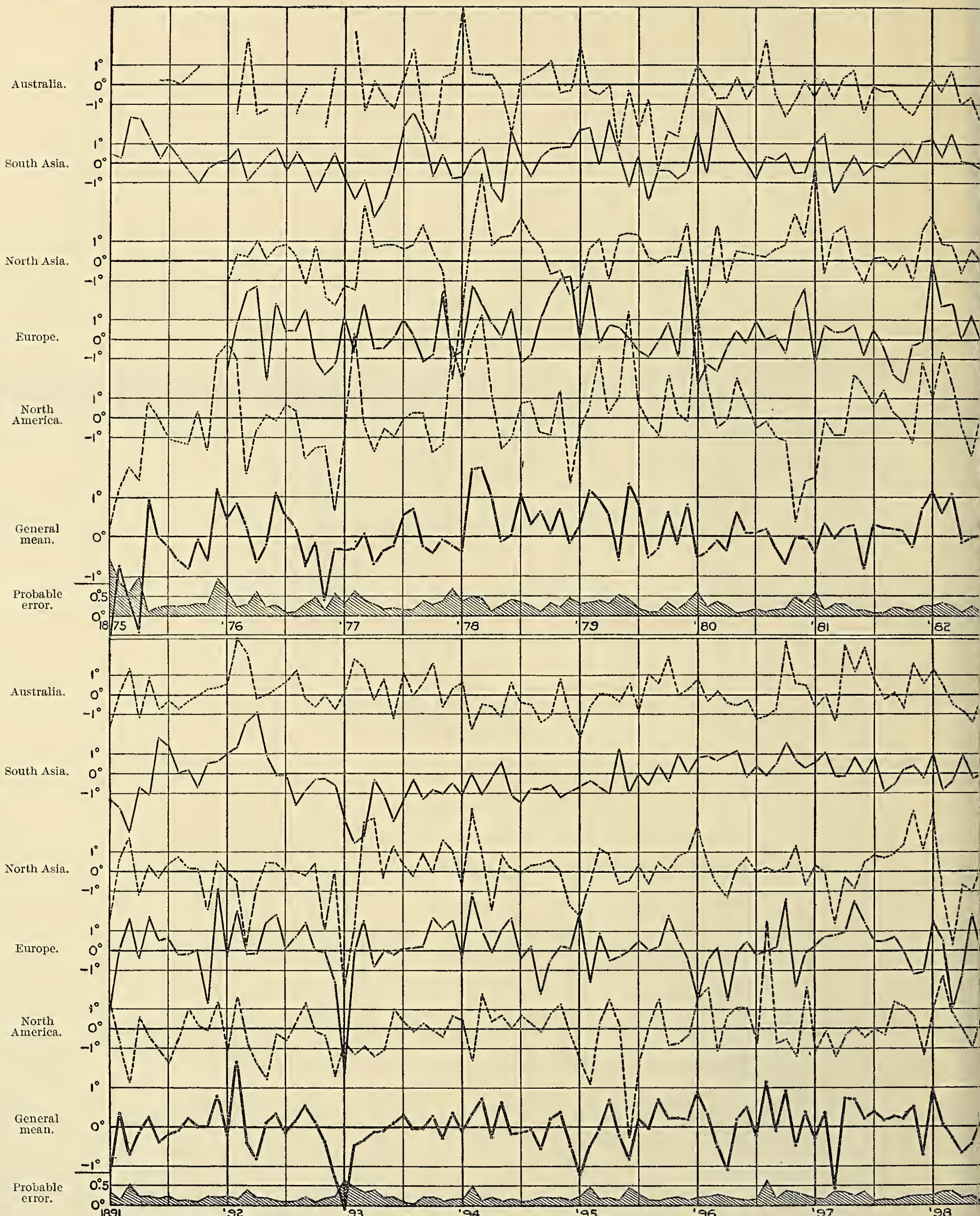
We may use another comparison. Let us omit the three groups, northern and southern Africa and South America, as including too few stations to have adequate weight. There remain the five large groups, North America, Europe, northern Asia, southern Asia, and Australia, each covering an enormous area, and with the centers of the several groups separated one from another by thousands of miles. Let the several mean monthly departures of these groups be assigned equal weight. We may now inquire what is the number of times that the mean departures would be found all positive, four positive, three positive, two positive, one positive, or all negative, respectively, according to the laws of probability of accidental variation; and let us compare these results with the number of cases found in reality. In this comparison months when less than five groups are included in Table 41 will be rejected, and zero departures will be counted as half positive and half negative. Fractional divisions thus resulting will be counted as half belonging to the group above, half to that below.

	Observed.	Computed.
Five positive..........	18	9.6
Four positive...........	57	48.0
Three positive.........	104	96.0
Two positive...........	84	96.0
One positive...........	42	48.0
Zero positive..........	3	9.6

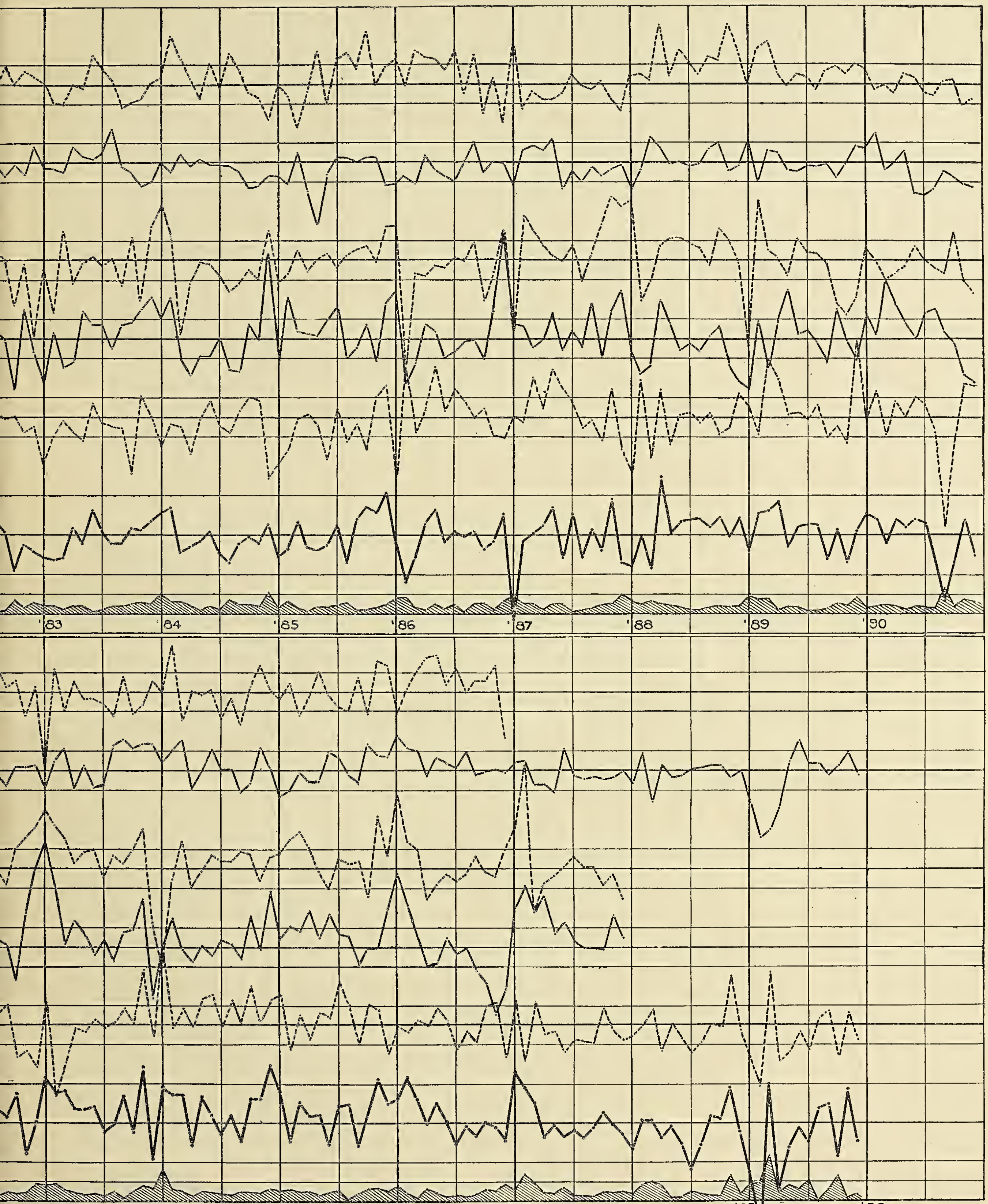
There is a difference between the actual arrangement of the departures and that which agrees with the theory of accidental variations. If the reader is inclined to throw five coins at a time for 308 times he will find that the arrangement of heads and tails will fall much more closely to that computed from the theory of probability than the temperature departures do. But in the case of the temperature departures the magnitudes ought to be considered as well as the signs, and there is nothing corresponding to this in the coin experiment, so that perhaps the two cases are not justly comparable. Indeed, it is perhaps impossible to devise a criterion which will prove to all minds whether or not there have been temperature departures not attributable to purely local causes. Apart from the magnitude of the "probable error" the most influential circumstances should be whether or not the fluctuations of the general mean appear to be gradual or wholly haphazard, and how many of the weighty group means combine to produce each gradual progression of the general mean.

In order to show to the eye the fluctuations in the general mean values given in Table 41, and how far the five principal groups of stations have united to indicate warmer and cooler periods as general over the earth's surface, Plate XXV is given. The first five alternately dotted and full lines follow the changes in the mean departures for the five principal groups as given in Table 41. The heavy full line gives the fluctuations of the general mean, and the cross-hatched area below indicates the magnitude of its "probable error." The reader will note that the scale of ordinates for the general mean and its "probable error" is twice as extended as that for the group means.

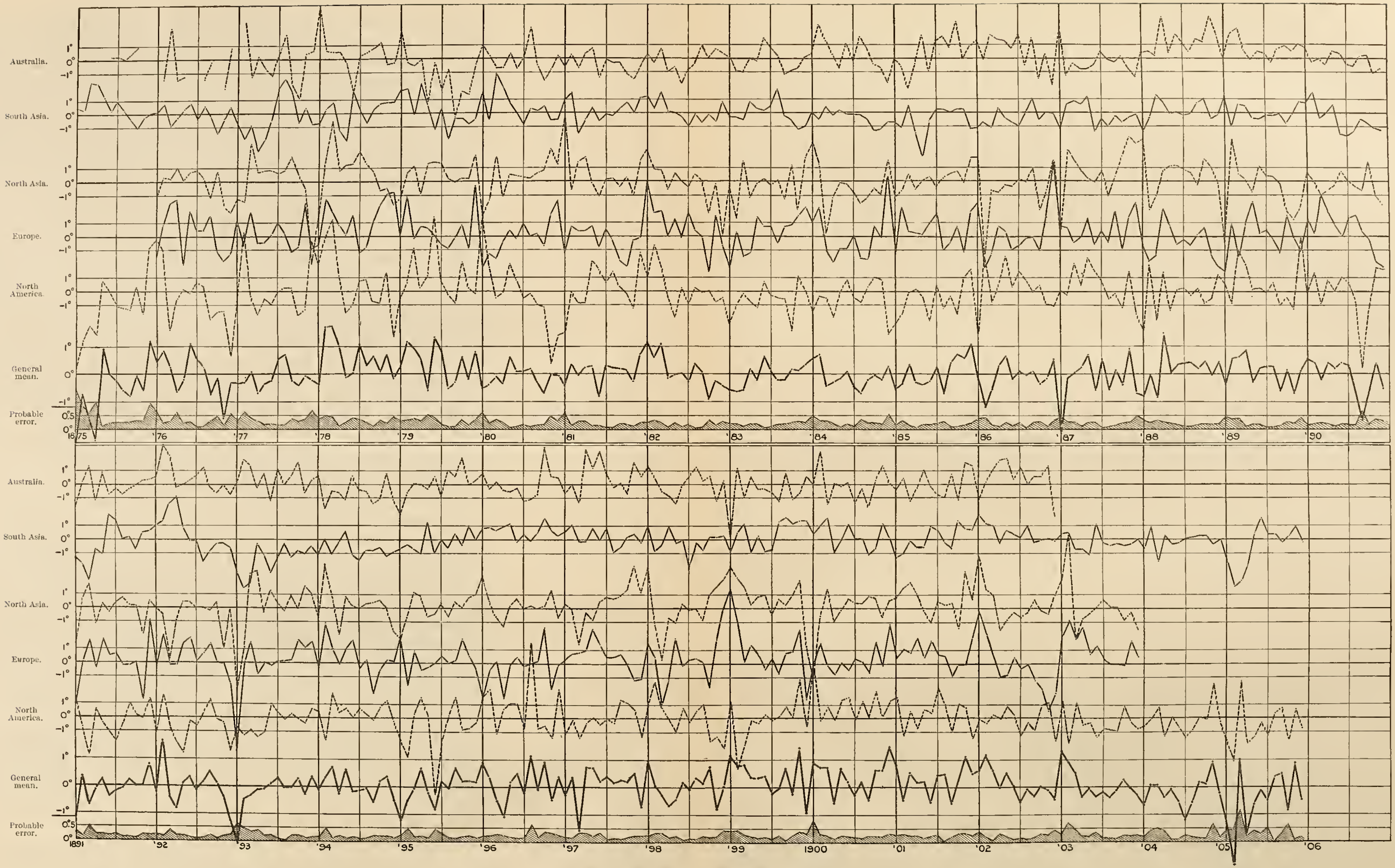
The local variations of the general mean are in many cases well marked, and are of the order of magnitude which, as already determined, can be expected to follow changes in the solar radiation of several months in duration and from 5 to 10 per cent in magnitude. Admitting without question that these observed variations of temperature do not prove the existence of fluctuations of such periods in solar radiation, they at least tend to strengthen a belief in the possible existence of such solar changes, which may be based principally on the results given in Part I. One of the best established instances of temperature fluctuation occurred in 1903 at the time when a corresponding change of the solar radiation was observed, as stated in Part I. There is a temperature fluctuation nearly simultaneous with the sun-spot cycle, as appears from Plate XXV A, in which the average yearly departures of temperature (line 2), as computed from Table 41, are compared with Wolfer's sun-spot relative numbers (line 1). The average temperature appears to be above the mean at sun-spot minimum, so that the solar radiation is more intense at sun-spot minimum. A change of 100 sun-spot numbers appears to produce a change of temperature of about 1° C. In view of what has been said in the early part of this chapter, a change of temperature of 1° C. would probably require a



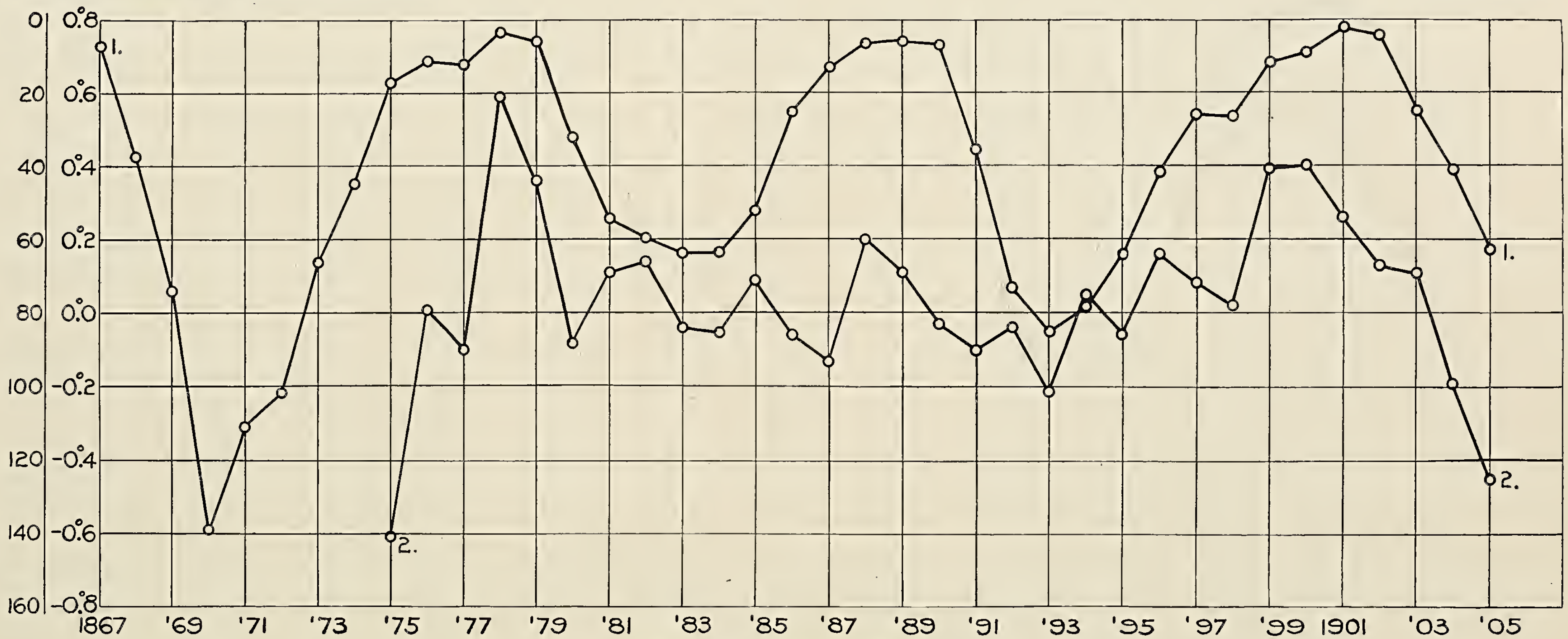
MONTHLY MEAN TEMPERATURE



-partures of Inland Stations.



MONTHLY MEAN TEMPERATURE DEPARTURES OF INLAND STATIONS.



Sun-spots and Earth's Temperature.

change of between 1.4 and 4.5 per cent in the intensity of solar radiation, depending on the length of time involved. The lower limit just assigned is far greater than that which can be directly attributable to the observed darkness of sun spots themselves, for their average total area corresponding to 100 sun-spot numbers is only about $\frac{1}{500}$ of that of the whole solar disk; so that, considering their average radiation three-fourths of that of an equal photospheric area, the direct effect of sun spots is only to diminish the solar radiation by perhaps $\frac{1}{20}$ per cent. We must therefore suppose that a change in solar radiation, while it may be simultaneous with a variation in the sun-spot numbers, is not limited to the area of the spots themselves, but is very likely caused by the obscuring of the sun's envelope by cooler vapors or other matter more prevalent during the presence of spots.

PART III.

THE RADIATION OF DIFFERENT PARTS OF THE SUN'S DISK.

THE RADIATION OF DIFFERENT PARTS OF THE SUN'S DISK.

INTRODUCTION.

The investigations of Vogel, Langley, Pickering, Wilson and Rambaut, Very, and others on the distribution of radiation over the sun's disk, and the various interpretations of their results, especially as relating to the thickness of the envelope which absorbs the solar radiation nonselectively, and as to the total amount of this absorption, are well known. Wilson and Rambaut in 1892 proposed to continue observations of the intensity of the solar radiation over different parts of the sun's disk with a view to determine whether or not there appeared to be a change in the transparency of the absorbing envelope, and if found, whether such variation appeared to be connected with the sun-spot cycle. Apparently, however, they did not continue this research.

Preliminary work of the kind was begun at this observatory in 1901 under Mr. Langley's direction, and it was in connection with the proposed installation of a long focus horizontal telescope for the purpose that there were made at the observatory the experiments on the effect of stirring the column of air traversed by the solar beam, which he described in his paper entitled "Good Seeing."[1]

When, in 1903, it became a matter of some degree of probability, as indicated by determinations of the "solar constant," that there may be frequent fluctuations of the amount of solar radiation, efforts were at once made to secure under uniform conditions frequent observations of the distribution of radiation along the diameter of the solar disk. There was installed for this purpose a horizontal reflecting telescope of 140 feet focal length, and beyond its focus a spectrobolometric outfit was provided, so as to measure the intensities of different spectral rays separately. The measurements have been continued at Washington up to the present time. During the expedition of 1905 to Mount Wilson, several days of observation were devoted to this work, and by Mr. Hale's kindness the Snow telescope was employed to furnish the solar image. In 1906 Mr. Hale included similar work in the regular routine of the Mount Wilson Observatory and placed the observations in the hands of Mr. Palmer, of the staff there. Messrs. Abbot and Ingersoll aided Mr. Palmer in providing and arranging the apparatus for this purpose and in making the earlier observations, and several pieces of the apparatus used were loaned from the Smithsonian equipment. Mr. Palmer continued to make almost daily observations from early in August to late in November, 1906, and Mr. Hale has kindly made his unpublished results accessible to us.

[1] American Journal of Science, Series IV, Vol. XV, p. 89, 1903.

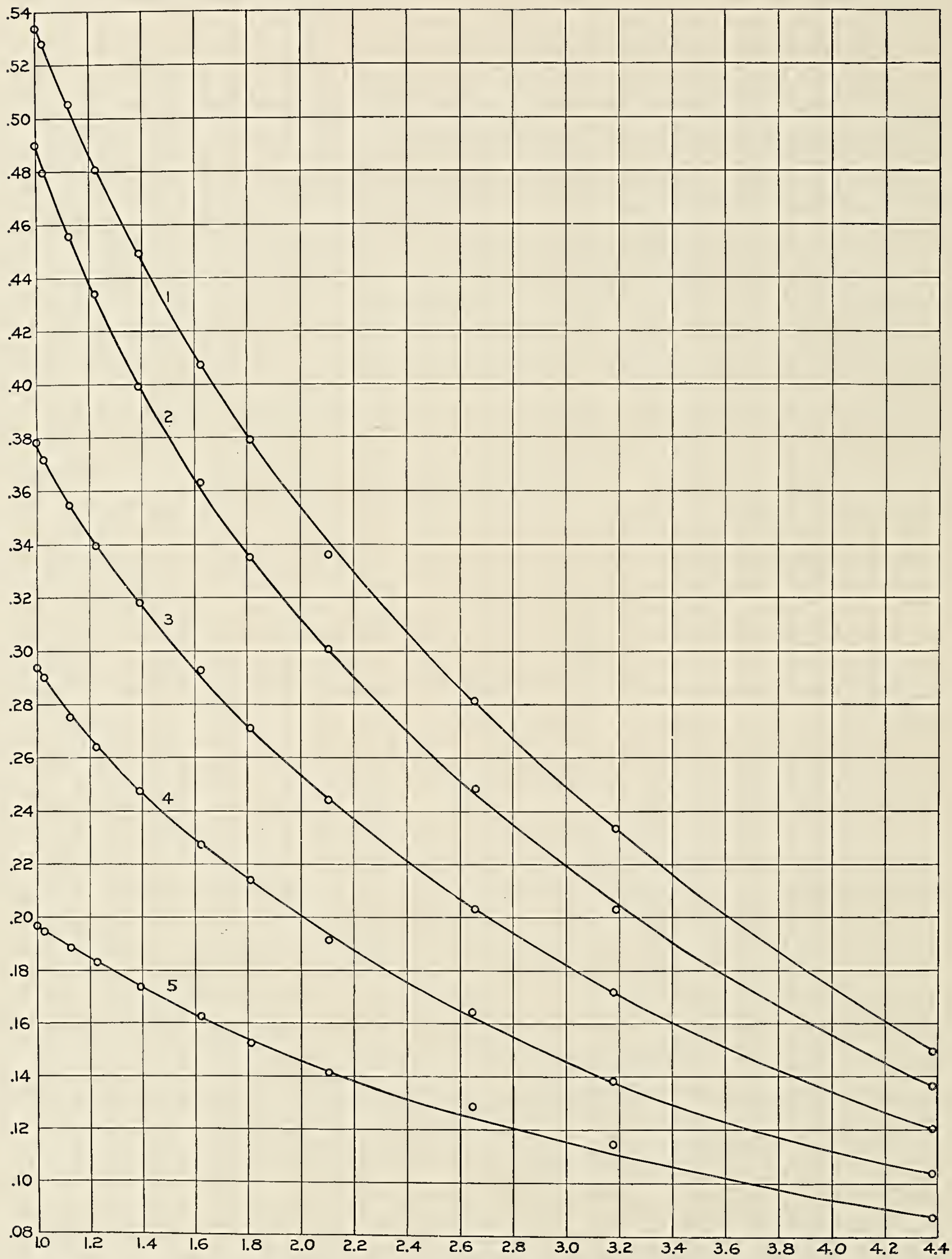
Chapter I.

THE PHENOMENON OF VARYING BRIGHTNESS OF THE SOLAR DISK, AND POSSIBLE EXPLANATIONS OF IT.

The sun does not appear uniformly bright from the center of its disk to its edge when observed photometrically, but decreases in brightness steadily and at a gradually increasing rate, so that at a point 95 per cent out on the radius of the solar disk the visual brightness is not far from 50 per cent of that at the center. If examined with the aid of a spectroscope, the decrease of brightness is found to be far more rapid for violet rays than for red, and spectrobolometric observations show that there is on the whole a continuous decrease of contrast between the brightness of center and edge as we observe rays of greater and greater wave-length.

These facts remind us of the effects produced by the earth's atmosphere on solar radiation; for when the sun is near the horizon and its rays traverse the atmosphere obliquely, the sun's brightness appears much less than it does at noon, and the enfeebling effect produced by the atmosphere is much greater for violet rays than for red ones. This analogy has led to the hypothesis that the variation of brightness over the sun's disk may be principally an effect either of scattering or of true nonselective absorption, produced by the presence of a gaseous layer of relatively lower temperature, superposed on what may be termed the radiating surface of the sun. At the center of the solar disk the rays of the photosphere would come by the shortest possible path through this assumed absorbing layer; but near the limb they would, of course, traverse it obliquely, so that the diminished brightness could be regarded as the effect of increased length of path in the supposed absorbing layer. There is, however, presumably a decided difference in the circumstances of the earth and the sun as regards the temperature of the absorbing layer, so that while in the visible region of the spectrum the atmosphere of the earth emits no appreciable radiation itself there is no certainty that the supposed absorbing envelope of the sun does not itself emit visible rays, and, indeed, it is highly probable that it does so.

Accordingly, the phenomenon of decrease in brightness from the center to the edge of the sun's disk can not be supposed to be solely a matter of absorption or scattering like that in the earth's atmosphere, but is probably a complex effect of combined radiation and absorption, whose nature we must regard in different



The Simple Exponential Formula and the Brightness of the Solar Disk.

aspects according to our theory of the sun and its surroundings. The question is further complicated by the fact that while there is, as we have said, a gradual increase of apparent absorption of the solar envelope with decreasing wave-length, there is, besides, in the spectrum the selective absorption of the gases of iron and other elements, and this absorption spectrum is well known to be a substantial reverse of the emission spectrum of the apparently thin chromosphere.

Most gases are generally thought to produce merely line spectra, whether of emission or absorption, so that the apparent general absorption of the solar envelope, which is not confined to Fraunhofer lines, would then seem to be probably an effect of scattering of light similar to that in our atmosphere, and not of true absorption. In this case it might at first sight be expected that it could be represented quantitatively by an exponential or logarithmic formula connecting intensity and length of path, just as the scattering of our atmosphere is represented by Bouguer's formula or its logarithmic equivalent. For the emission and absorption phenomena would be expected to be confined to the rather narrow Fraunhofer lines and bands, and the apparent absorption of the remainder of the solar spectrum might be a phenomenon of scattering alone, and irrespective of the temperature of the gases. In order to test this hypothesis, some assumption has to be made as to the thickness of the absorbing envelope, and as most astronomers regard the reversing layer as thin compared to the radius of the sun, we naturally first make the same assumption for the layer which produces the apparent general absorption.

Assuming a thin scattering layer, the length of path of a ray traversing it directly from sun to earth is approximately proportional to

$$\frac{1}{\sqrt{1-\left(\frac{B}{R}\right)^2}}$$

where $\frac{B}{R}$ is the fraction of the solar radius lying between the point of observation and the center of the disk. Let the intensity of such a ray be d, the percentage of it transmitted by the scattering medium for vertical incidence be a. Then the distribution of directly transmitted rays along a radius of the sun's disk should be expressed by the formula

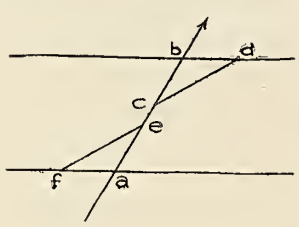
$$\log d = \frac{1}{\sqrt{1-\left(\frac{B}{R}\right)^2}} \log a + \text{constant}$$

if the view we have spoken of properly represents the condition of affairs on the sun.

But this formula by no means would account for the observed distribution of radiation, for, as shown for five different wave-lengths in Plate XXVI, the curves of observed variation of intensity along the sun's radius are not transformed into straight lines by plotting logarithms of intensities as ordinates against the values of the expression

$$\frac{1}{\sqrt{1-\left(\frac{B}{R}\right)^2}} \text{ as abscissæ.}$$

On a more careful consideration we ought not to expect this simple formula to represent the observed facts; for there is no account made in it of any radiation excepting that of the direct beam. Consider again the analogy presented by the earth's atmosphere. As is shown in Chapter III of Part II of this book, we find from observations of October 18 and 19, 1906, made on Mount Wilson, that if the sun stood in the zenith its radiation would be changed as follows in passing through the atmosphere: Directly transmitted, 85.7 per cent; absorbed by water vapor and oxygen, 6.1 per cent; scattered to the earth's surface by the atmosphere, 6.2 (?) per cent; scattered toward space by the atmosphere, 2 (?) per cent; absorbed nonselectively in the atmosphere, 0 (?) per cent. If, then, the diffusely scattered radiation of so thin a gaseous envelope as that above Mount Wilson amounts to a tenth of the directly transmitted radiation, what should be expected as to the magnitude of the diffusely reflected ray as compared with the ray directly transmitted by an envelope of gas possibly fifty times as thick, like the reversing layer on the sun? Evidently the diffusely scattered light is probably a very considerable proportion of the whole. Part of it, of course, must be reflected diffusely back toward the sun, but the greater part must be reflected diffusely toward space. If the diffusing envelope is regarded as symmetrical about the center of the sun the diffuse reflection will also be symmetrical, in the sense that equal angular areas of space will receive equal amounts of diffuse reflection.



It seems clear, then, that there can be no soundness in an hypothesis of the distribution of intensity of light along the solar radius which deals only with direct rays and ignores the rays diffusely reflected by the so-called absorbing envelope, for these latter form no insignificant part and may form the major part of the solar beam. We then have to consider the probable distribution of intensity of the diffusely reflected rays over the sun's disk. Referring to the accompanying text figure, let *af* represent a surface emitting radiation in all directions and consider a ray of one single wave-length emitted in the direction *ab* making the angle *z* with the normal to the surface. Let the parallel surface *bd* form the upper boundary of a layer of medium filling the space *adbf*, and let this medium contain a gaseous or other substance made up of very numerous molecules or particles, all small as compared with the wave-length of light and uniformly distributed. Let this medium exercise no true absorption upon radiation of the wave-length in question, whatever selective absorption it may exercise on rays of certain special wave-lengths, but let it produce a scattering of light like that treated by Hon. J. W. Strutt (Lord Rayleigh) in his paper on the light of the sky (Philosophical Magazine, vol 41, p. 107, 1871). Of the ray *ab* a certain portion will undergo scattering at *c* and emerge from the medium at *d*. But for every ray like *cd* scattered out of the direct beam and leaving the medium finally through the surface *bd* there will be a ray *feb* scattered into the ray *ab*, and which will leave the boundary at *b* in exactly the same intensity that the ray *cd* leaves it at *d*. A similar consideration holds for any number of cases of scattering to which a ray may be subjected, whether they be primary or secondary or of still higher order. It is only those rays which are finally scattered back across the rear boundary *af* which are lost to the beam *ab* without compensation.

Let p be the coefficient of vertical transmission across the layer *adbf* for a direct ray of the given wave-length, and let A_0 and A represent, respectively, the intensities of the direct ray *ab* at *a* and at *b*, not counting at *b* the reinforcements of rays scattered into the beam.

Then $A = A_0 p^{\sec z}$ and $A_0 - A = A_0(1 - p^{\sec z})$.

The latter expression is equal to the entire loss of rays from the beam *ab* by scattering, for we have assumed that there is no absorption in the medium. Of the scattered radiation $A_0(1-p^{\sec z})$ a certain proportion, which we may call x, will pass out of the medium through the front boundary, and the remainder $(1-x)$ will be scattered back across the rear boundary. But, as shown above, the proportion x is compensated for exactly. Hence the total intensity of the beam *ab* at *b* is

$$A_0 p^{\sec z} + A_0 x(1 - p^{\sec z}) = A_0\{x + (1 - x) p^{\sec z}\}.$$

The quantity x should be determined as a function of p and z (and this is a problem in mathematics toward whose solution Lord Rayleigh has contributed greatly) before the formula can be capable of application in connection with observations of the apparent absorption of the solar envelope.

Unfortunately we have not been able to obtain a solution of this problem and we must leave it to other hands. If we assume, however, that x is constant, as, for instance, $\frac{1}{2}$, then the resulting distribution of intensities over the solar disk may be made to fit almost exactly the observed distribution of infra-red rays by choosing a proper value of p; but of course it is obvious that x must be a function which decreases as z increases. The inference may be drawn that the deeper layers of the sun's interior contribute no radiation toward space, and probably those only slightly below the base of the chromosphere begin to contribute for beams emerging nearly vertically to the surface, but are unable to contribute to the oblique rays.

More and more oblique rays are furnished by the layers nearer and nearer the surface. Hence, the rays coming from very near the limb are to be considered as coming from cooler, because more exterior, sources, and this accounts for their deficiency in rays of the shorter wave-lengths. We then incline to suppose that the apparent "absorption of the solar envelope" may really be a phenomenon of emission from sources of different temperatures, but caused by the scattering produced within a thin layer of gas which may be the reversing layer. Referring to Chapter IV, Part II, an analagous phenomenon would be presented by the appearance of the earth to an eye which could see only by rays of very great wave-length.

It seems clear that if the outer part of the sun is of a gaseous nature and of anything like the density of our atmosphere the scattering which must necessarily occur within the solar boundary must prevent the possibility of seeing directly down into the sun by more than perhaps 1 per cent of the solar radius, or about the thickness of the reversing layer, so that the sun, though gaseous, presents a fairly sharp boundary. This consideration, therefore, is adapted to explain the apparent conflict between the observed solar conditions of excessively high temperature and fairly sharp boundary, which are explained by some in accordance with the refraction theory of Schmidt and neglected by those who suppose the photosphere to be a cloudy layer, notwithstanding that it is 6,000° or more in absolute temperature. It seems to us of little importance what course within the sun the solar rays are influenced by refraction to pursue, because they probably become almost wholly scattered to other directions before traversing a distance of more than perhaps 1 per cent of the sun's radius. We are aware that these views may be opposed on the grounds, first, that the density of the gases of the sun's exterior layers may be much less than we have assumed, and, second, that our knowledge of the exact amount of scattering which is caused by the gases of the earth's atmosphere is too slight to admit of confidence in our inferences regarding the scattering in the sun. We believe that these questions will be well worth investigation.

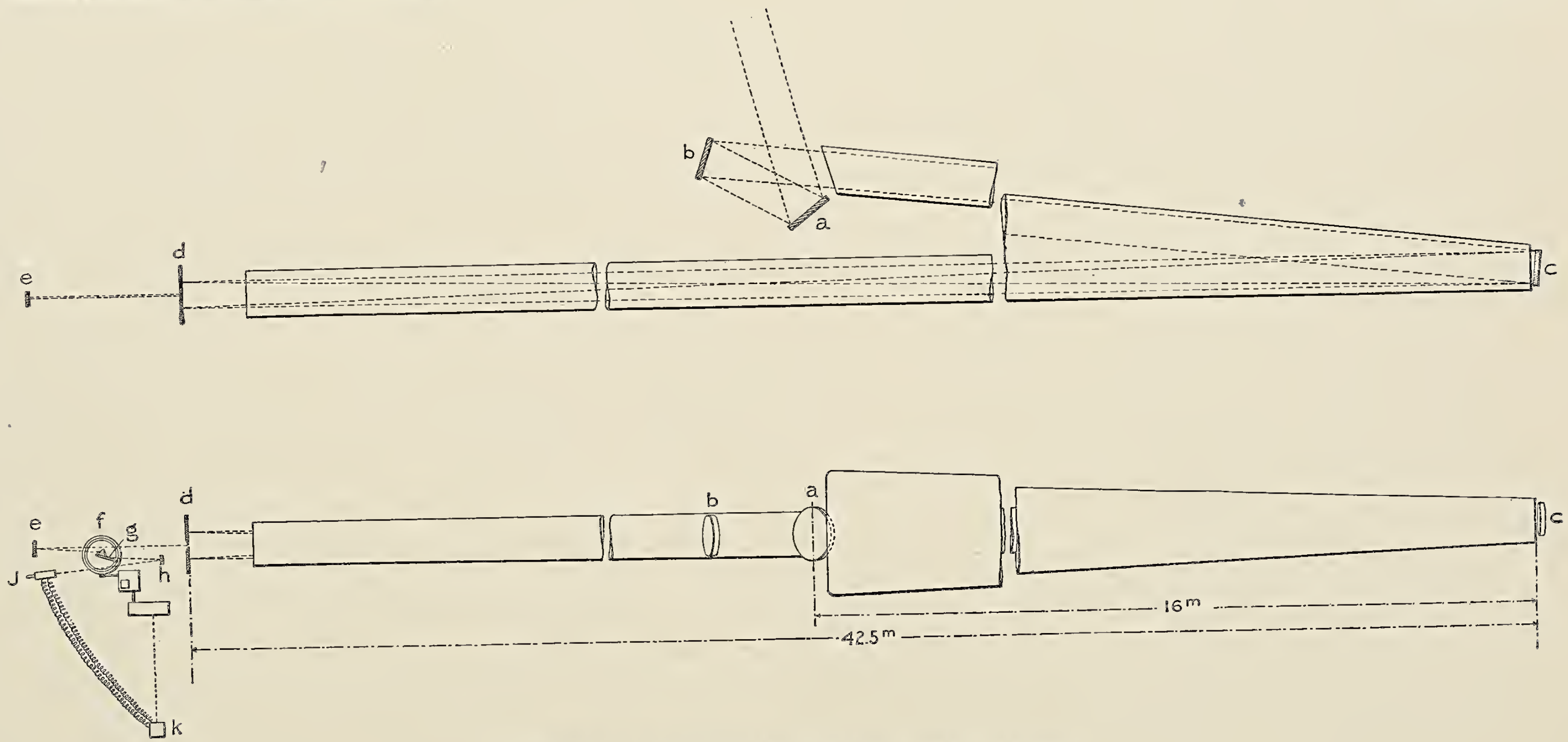


Diagram of the Apparatus for Observing the Solar Image.

Chapter II.

ARRANGEMENTS FOR OBSERVING THE DISTRIBUTION OF RADIATION OVER THE SUN'S DISK.

APPARATUS.

1. THE HORIZONTAL TELESCOPE.

The first requirement for observing the distribution of radiation over the sun's surface is a large solar image of sufficient intensity and good definition. As it is inconvenient to move the complicated observing apparatus, the solar image is preferably a fixed one, and a cœlostat or siderostat is required. We have preferred the cœlostat because it gives a nonrotating field. The reader is referred to Chapter II of Part I for a description of a cœlostat having a second mirror mounted south of the rotating mirror so as to reflect a beam northward. The same combination has been employed with the horizontal telescope about to be described, but two different cœlostats have been employed, one with a rotating mirror of 30 inches diameter and a secondary mirror of 18 inches diameter; the other, used in all the work since 1904, has a rotating mirror 17 inches in diameter and a secondary mirror 12 inches in diameter. The former instrument is better adapted to the work, excepting that it is more inconvenient to remove and resilver its large mirrors; but owing to pressing work for the Mount Wilson expeditions, the large instrument has never been set up since it was exhibited at St. Louis in 1904.

From the cœlostat the rays pass northward through a double-walled metal tube, shaded by a tent, and fall upon a concave mirror of 20 inches diameter and 140 feet focus, which reflects the rays southward and underneath the cœlostat through a shaded double-walled metal tube to the solar image. The course of the beam is shown in Plate XXVII, from the cœlostat mirrors *a*, *b*, through the branch tube to the concave mirror *c*, and thence through the long horizontal tube to the focus at *d*. The mirror *c* is movable in a north-and-south direction so as to adjust the focus at *d*.

It is well known to all who have ever examined the solar image of a large telescope that the phenomenon called "boiling" often impairs the definition. This defect is no doubt chiefly caused by the variations of density in the air, produced by changes of temperature. Star images often show "boiling," but the sun's image is subject to it in a very much greater degree, and plainly for the reason that when the sun shines there is a large supply of radiation to heat the earth's surface, causing streams of heated air to rise across the path of the rays. It is well known by solar observers that the early morning hours and calm days when the sky is very hazy or even thinly clouded are favorable times to secure good solar definition; and this is probably because there is at such times less heating of the earth's surface by the sun, and therefore less rise of heated air currents. But in the work we are about to describe we have not been able to avail ourselves of these times of "good seeing." Buildings interfere with seeing the sun from this observatory in the very early morning hours. During hazy or cloudy days there is so much fluctuation of the atmospheric transmission that the results which could be obtained at such times by comparing the brightness of different parts of the sun's disk would be worthless. Accordingly, we have been compelled to confine our studies to the hours when the sky is clear and when the sun is high, although "boiling" is then apt to be at a maximum.

Experiments were begun in 1902, under Mr. Langley's direction, to produce by mechanical means "good seeing" through air otherwise productive of "boiling." These experiments were described by him in a paper entitled "Good Seeing."[1] His scheme of operations consisted in vigorously stirring the column of air traversed by the rays, in order to break up and mix thoroughly the parts of differing density. Very satisfactory results were obtained in the preliminary experiments on an artificial star. Indeed the "boiling" of the solar image itself was perceptibly reduced by stirring the air in the tube of the horizontal telescope employed to produce it, although it was recognized at the time that the larger part of the "boiling" is introduced in the path of the rays before they reach the cœlostat, so that the provision of perfect optical conditions thereafter can not remedy the whole defect. Trials were made of the utility of a tube about 50 feet in length, in which the air could be stirred, pointing toward the sun from the cœlostat, and this was found to be of such decided advantage that the impression prevailed in the minds of the observers that the major part of the "boiling" is often produced within reach of mechanical means of mixing the air, and that the effect of mixing it is very beneficial.

When the long-focus horizontal telescope was introduced in 1904, provision was made for mixing the air within its tube in the same way that had proved successful in the preliminary experiments, namely, by introducing alternately on opposite sides of the tube air ducts for compression and exhaustion, respectively, which were connected to the outflow and intake pipes of a rotary fan blower, as shown in Plate II. Whether the apparatus was not sufficiently powerful or not well adapted for so large a telescope tube, at any rate the results of this installation have never been as satisfactory as those obtained with the smaller apparatus described in Mr. Langley's paper on "Good Seeing." The urgent requirements

[1] American Journal of Science, Series 4, Vol. XV, p. 89, 1903.

of the Mount Wilson expeditions prevented trials of further improvements which were contemplated, so that although the experiments of 1902 convinced us that decided improvements of midday seeing are as possible as they are desirable we are not yet in position to state exactly how they are to be secured, but hope to continue work along these lines.

Another defect of solar definition is frequently produced by the heating and bending of the mirrors employed in the horizontal telescope. It would doubtless be easier to get good definition with an equatorial refracting telescope than with the horizontal reflecting telescope employed, first, because the rays would not traverse so long a path near the ground, second, because only one glass instead of three would be subject to the heating of the solar rays, and, third, because the bending of a lens would produce less distortion than the equal bending of a mirror. If a new installation for the purpose of bolometric work on the solar image should be proposed, it would be worth considering whether the inconveniences of the equatorial mounting, with its long movable tube, the changes of focus between different wave-lengths, and the required movements of the complex observing apparatus, would not all be outweighed by the prospect of greatly improved definition.

In practice the definition of our great horizontal telescope is generally fairly good, but sometimes very bad. Considerable changes of focus often occur while the mirrors are rising in temperature. It is not probable that the defects of the image are sufficient to be a serious source of error in the work of determining the comparative distribution of radiation along the diameter of the solar disk as it is now being carried on, but they are too great to permit of useful work being done on the finer details like the faculæ and the smaller sun spots.

2. THE SPECTROBOLOMETRIC APPARATUS.

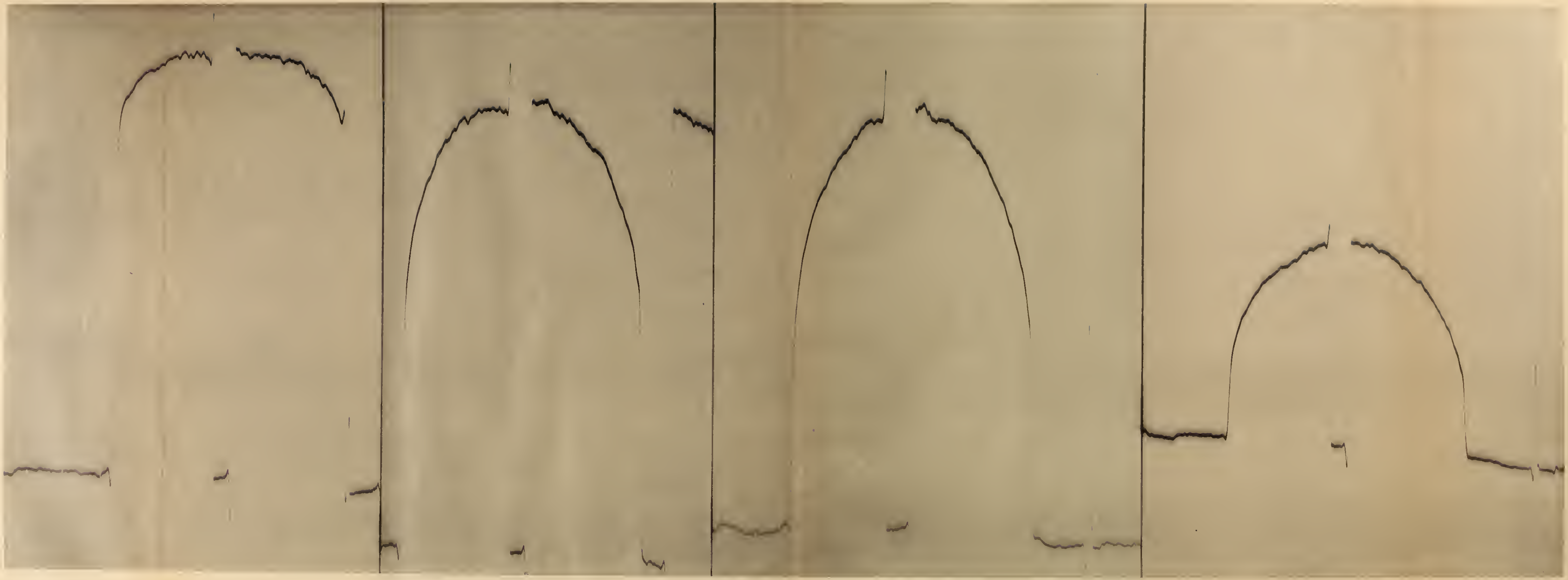
Referring to Plate XXVII, the solar image is formed by the horizontal reflecting telescope upon the plane of the jaws of a slit *d*, whose height is 2.1 cm., and whose width is governed to suit the intensity of the rays of different wave-lengths examined, and is thus changed by steps between the limits 0.2 mm. and 2.0 mm. to suit the energy of different parts of the spectrum. A grill diaphragm is sometimes placed across the slit to further reduce the intensity of the beam at some points of the infra-red spectrum.

After passing through the slit the rays fall upon a concave mirror *e* of 2.30 meters focal length, by which they are made parallel, and are reflected toward a 60° glass prism *f*, with faces 4 cm. square. A plane mirror *g* reflects the rays thence to a concave mirror *h* of 0.75 meters focal length, by means of which the spectrum is brought to focus upon the bolometer at *j*. The sensitive strip of the bolometer employed is 7 mm. long and 0.6 mm. wide, and is contained in an air-tight case with a very thin glass cover. For the present purpose the case is not exhausted, but is air-tight, and advantage in steadiness results from the prevention of communication of pulses of the outside air to the bolometer. The bolometer communicates with a galvanometer *k*, whose indications are recorded upon a moving plate after the manner described in Chapter II of Part I.

METHOD OF OBSERVING THE DISTRIBUTION OF THE INTENSITY OF RADIATION OVER THE SOLAR DISK.

Langley and others who have examined the distribution of energy over the solar disk have generally made settings upon selected points of the image of the sun. We have generally preferred to stop the cœlostat at each exposure, and thus to allow the image to drift by the diurnal motion of the earth, so that the disk of the sun travels steadily across the slit of the spectrobolometer, and thus the rays from all the parts of a band extending across the center of the disk are brought in succession to the bolometer. The slit is at right angles to the direction of motion of the solar image, and is so short as compared with the diameter of the image that the bolometer in this way serves to indicate the distribution of intensity of a selected wave-length of light along a diameter of the solar disk. The advantage of this method of investigation is this, that there are no errors of following or of unequal transmission of different parts of the optical apparatus to allow for. As no change of the mirrors of the horizontal telescope is made during a single run across the slit, it is clear that every point of the sun, as it reaches in the heavens that point toward which the optical axis of the telescope points, is treated by the mirrors in exactly the same way as every other point of the sun which has come, or will come, to the same situation, so that the distribution of energy as observed by the bolometer is independent of whether the cœlostat is exactly adjusted to fill the concave mirror with light, or whether some obstacle cuts off a part of the beam, or some inequality of silvering makes one part of a mirror more efficient than another. The spectroscope is of course fixed during each run, and it is customary to allow the sun to drift across the slit two or three times at a single wave-length before passing on to a new part of the spectrum. Observations are made at six or eight different wave-lengths, chosen to indicate the behavior of the whole spectrum between wave-lengths 0.40μ and 2.0μ.

The result of such a procedure as has just been described is to produce upon the photographic plate, which moves steadily in front of the galvanometer, a record of the exposure of the bolometer first to the sky, then to the limb and succeeding points on a diameter of the sun, and finally to the sky again, so as to produce an energy curve similar in form to the letter U inverted. Such curves are shown in Plate XXVIII, which includes records for wave-lengths 0.433μ, 0.534μ, 0.699μ, and 2.097μ. When the image of the sun has drifted about halfway across the slit, it is customary



BOLOGRAPHIC ENERGY CURVES, TAKEN ALONG THE DIAMETER OF THE SOLAR IMAGE.

to insert a dark shutter in the beam at the cœlostat, so as to give a zero of radiation to aid in the reduction of the observation. The deflection of the galvanometer at such times is usually found to be apparently identical with that produced by the radiation of the sky, so that the intensity of the radiation scattered by the sky, even in the closest proximity to the limb of the sun, is very small as compared with the intensity of the direct solar beam. When the shutter is inserted there is no question to be considered of the radiation proper to a body at a low temperature, because the glass prism of the spectrobolometer is opaque to such radiation, and even if it were not, would refract it to a different place in the spectrum.

Professor Julius, in an article on observations made by him during the eclipse of 1905,[1] has drawn attention to the radiation of the sky as a source of error in measurements of the kind here being described; but the examination of the comparative effects of the sky radiation and of the absence of radiation during the interposition of a shutter shows, we think, conclusively that the effect he speaks of is entirely negligible in our observations. If there were, in fact, an error of the kind he speaks of, its magnitude would presumably be different according as the observations were conducted on Mount Wilson or in Washington. It will appear from the results to be given presently, that if there is any difference of this kind, it is too small to be evident by comparison of the observations at the two stations.

One object of the work is to detect changes from time to time in the distribution of radiation over the sun's disk, and we now come to discuss the best way of doing this. The time required for the solar image to drift over the slit of the spectrobolometer varies from day to day, and the width of the bolographic record as measured on the plate alters correspondingly. Furthermore, the sensitiveness of the bolometer, the drift of the galvanometer, the degree of clearness of the sky, and the length of path of the beam in the earth's atmosphere being all variable, it follows that the heights of the curves also vary. Hence it is not possible to match the curves by superposing them for the purpose of detecting changes in form, and they must first be measured and reduced to some common scale for comparison.

We are accustomed to measure the heights of the curves at the center and at several pairs of points equidistant from the center on each side. An illustrative example of these measurements will be found in the following chapter. The rate at which the photographic plate is moved by the clockwork is now determined on each day of observation, and this, with the data given in the Ephemeris, enables us to compute the width which corresponds on the plate to the diameter of the sun. Formerly (i. e., prior to May 11, 1906) we were accustomed to use, instead of this computed width, the apparent width as measured upon the plate between the two points where the ordinates were 4 per cent of the maximum ordinate of the bolo-

[1] Astrophysical Journal, vol. 23, p. 312, 1906.

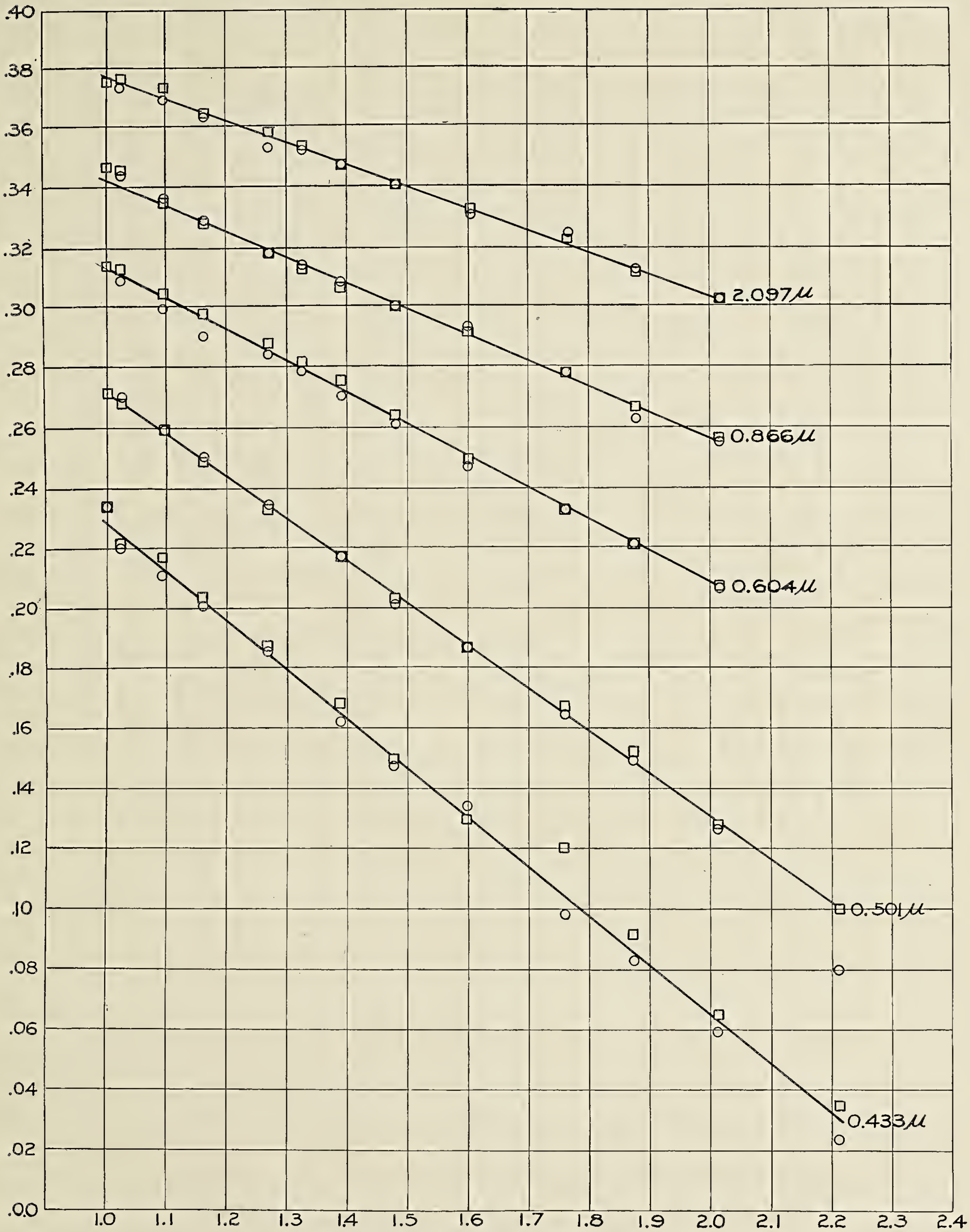
graphic record.[1] But there is a little uncertainty in this old method because the curve does not rise absolutely sharply, and its form depends on the time of swing of the galvanometer needle, the width of the bolometer, and on the tremor and "boiling" of the solar image, so that there may be appreciable error introduced in comparing observations of different days by such a process. Having computed the distance on the plate corresponding to the width of the solar image, the distances from the center of the bolometric records to the points of measurement may be expressed in fractions of the radius of the solar disk, so as to reduce them to a common scale for the comparison of results of different days. The several measured heights for each single curve might be divided by the height of the curve at the center, in order to reduce them to a common scale of ordinates, but this procedure would require us to place undue weight on the accuracy of the central part of the curve.

The convenience of the logarithmic plots, used in the "solar-constant" reductions described in Part I, has led us to adopt a mathematical expedient for converting the results of observation into straight lines whose inclinations to the axis of abscissæ summarize the data gathered. For this purpose we plot logarithms of observed heights of the curve as ordinates, and a certain function of the corresponding distances from the center of the energy curve as abscissæ. Let the half width of the record upon the plate, corresponding to the radius of the sun, be R; then the abscissæ taken for the logarithmic plot are computed by the formula:

$$4.76\left\{\sqrt{(1.21)^2-\left(\frac{\rho}{R}\right)^2}-\sqrt{1-\left(\frac{\rho}{R}\right)^2}\right\}$$

This apparently arbitrary function expresses the ratio of the lengths of path of two rays, one coming from a point on the sun whose apparent distance from the center of the disk is ρ and traversing an imaginary layer, situated just outside the photosphere, whose thickness is 21 per cent of the solar radius; the other coming from the apparent center of the disk and traversing the said layer vertically. The observations of all wave-lengths and for all values of $\frac{\rho}{R}$ less than 0.95 give close approximations to straight lines when plotted in this manner, as shown by the plots given in illustration in Plate XXIX. In these curves five different wave-lengths are represented each as observed on a single drift curve of May 17, 1906. Ordinates are logarithms of bolographic deflections. Abscissæ are the above-mentioned function of ρ. The advancing and following limbs of the sun are distinguished by squares and circles in the plot. The tangent of the angle of inclination

[1] A comparison has recently been made between the computed widths of a considerable number of drift curves and the widths at the 4 per cent points which were formerly used in the reductions. It proved that the widths formerly used were too great by an average difference of 0.0075. This correction has therefore been applied to all the observations reduced by the old method that are published in this volume.



Logarithmic Plots from Solar Drift Curves.

of the representative straight line is treated as being the logarithm of the apparent transmission coefficient of the solar envelope for the ray of light examined.

We attach no importance whatever to this procedure, except as a mathematical device for reducing the observations to a condition in which they may readily be compared together. It would be absurd to suppose that the phenomenon of variation of the intensity of radiation along a diameter of the solar disk is due to the imperfect transmission of a layer of matter which is homogeneous in density and optical quality, 21 per cent of the radius of the sun in thickness, and situated just outside the photosphere, and that only the direct beam would be of importance after traversing such a layer. We have merely adopted a particular scale of abscissæ for convenience in the graphical treatment of the observations in the comparison of one day's work with another.

In order to show more directly the results obtained, several of the best days have been reduced, also, by the following process: From the logarithmic plots obtained as just described the mean logarithms of the ordinates at the abscissæ 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, and 2.2 were read off. As will be seen by inspection of Plate XXIX, there can be but little uncertainty as to the proper reading at an interior position like abscissa 1.4, although there may exist more uncertainty of the proper reading at the abscissa 1.0, where only one observation is to be had, for this single observation may be defective, owing to temporary disturbance of the observing apparatus or from other causes. Accordingly a reading at the abscissa 1.0 is determined indirectly by obtaining from several curves of observation the mean difference of logarithms for the abscissæ 1.0 and 1.4, and adding this mean difference to the observed mean reading at abscissa 1.4. The observed logarithms at the several points are next subtracted from the computed logarithm at abscissa 1.0, and the numbers corresponding to the mean results for abscissæ 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, and 2.2 are then obtained.

The numbers obtained by the process just described represent the mean intensity of the solar radiation at points situated 0.000, 0.612, 0.772, 0.855, 0.908, 0.943, and 0.965 of the radius from the center of the sun's disk. These results and an illustrative example of the process of obtaining them will be found in the following chapter.[1]

SOURCES OF ERROR.

1. VARIATION OF ATMOSPHERIC TRANSMISSION.

On most days in Washington the transparency of the atmosphere is apt to change, owing to drifting smoke, dust, or clouds, so that during the interval of two minutes or more required for the solar image to pass over the slit of the spectro-

[1] Owing to a slight error in the original computations afterwards corrected, the fractions of the radius employed in the following chapter differ slightly from those just given.

bolometer, it frequently happens that the intensity of the beam of sunlight alters independently of any change in the sun. This leads to the rejection of some days of observation. We have generally made many observations on each day of working, so that these changes are thereby rendered less likely to influence the general result of a day.

It might be thought that there would be also a change of intensity caused by the change of length of path of the solar beam in the earth's atmosphere attending the change of solar zenith distance. But in fact there is no such thing to be met with in our experiments, because the axis of the telescope remains fixed during each observation, so that there is no change of zenith distance to be considered.

2. TIME OF SWING OF GALVANOMETER AND DELAY OF THE BOLOMETER IN REACHING A STATE OF TEMPERATURE EQUILIBRIUM.

When radiation is admitted to the bolometer a brief time must elapse before the galvanometer responds at all, and a longer time before it responds completely, depending on the time of swing of the needle, the rate at which the radiation increases, and the capacity for heat, the conductivity and emissivity of the bolometer. We have made experiments to determine the combined effect of these things at a time when the period of single swing of the galvanometer needle was about a half second greater than that usually employed. A shutter was arranged in such a manner as to cut off simultaneously the radiation falling upon the bolometer and a beam of light falling upon the photographic plate which records the galvanometer deflection, so that the position of the bolometric trace could be measured when known intervals of time had elapsed after the radiation had been cut off or admitted. In the following table are given the average times required to produce different percentages of the complete deflection. The result given is the mean of four closely agreeing trials, in two of which the radiation was admitted to the bolometer, and in two of which it was cut off.

Time elapsed in seconds......	0.10	0.35	0.50	0.65	0.77	0.90	1.04	1.22	1.40	1.61	2.10
Fraction of full deflection produced..................	.00	.10	.20	.30	.40	.50	.60	.70	.80	.90	1.00

From the results just given it seems probable that with the conditions ordinarily prevailing during the observations, the full deflection due to the admission or cutting off of a quantity of radiation would be produced within a time about equal to the time of swing of the galvanometer, or about 1.5 seconds.[1]

Recalling that the energy curve produced by the drifting of the solar image across the slit of the spectrobolometer is a symmetrical curve of the shape of an

[1] The measurements just given are reduced on the basis of the final deflection of the galvanometer as unity. The first swing of course exceeds the final deflection, and requires somewhat longer than the time above given for its complete execution.

inverted letter U, it is easy to see that the first half of the energy curve, corresponding to the advancing limb of the sun, will be recorded everywhere lower than it should be, and that corresponding to the following limb the curve will be everywhere higher than it should be on account of the action of the source of error we are considering. But these effects will be nearly unnoticeable to the observer, because their apparent result will be to shift the whole energy curve in position on the plate, and since there are no means used to indicate the exact time when the limbs of the sun enter and leave the slit, the fact of shifting is unrecognizable.

It is possible that a real change in the form of the curve, as well as a shifting, might also occur, but this must be very slight. A value far in excess of the real change of form may be determined as follows: We may assume that the observed form of the energy curve differs so little from its true form that if we determine the change which the error in question would produce on an energy curve of the observed form, the result would differ inappreciably from the change it would produce on a curve of the true form. The change which would be produced in the observed form will be less than that which would result by carrying every point of the curve forward a distance in abscissæ corresponding to one and one-half seconds of time. For starting at the center of the sun it is clear that the galvanometer deflection will have taken a value not in excess of the true one when one and one-half seconds have elapsed after the center of the disk has crossed the slit. But at that instant the energy is less by a certain small amount than the galvanometer indicates, and the galvanometer will respond fully to this difference of energy in one and one-half seconds more, so that the position of the galvanometer will certainly be at every instant not above what it should have been one and one-half seconds previously. In reality the deflection will be closer to the real curve than this procedure would indicate, because during each of the one and one-half second intervals considered, the force urging the galvanometer is greater than the force which existed at the beginning of the interval, so that the galvanometer deflection will fall at every instant lower than the real curve of one and one-half seconds earlier.

The discrepancy will be at its maximum for the short wave-length energy curves, because the rate of change of form is greatest for them. The mean energy curve for wave-length 0.433μ has been treated by projecting forward every point upon it by $\frac{1.5}{68}=2.2$ per cent of its half width, and the differences of ordinates thus produced have been read off for different fractions of the solar radius, and are given as fractions of the central ordinate in the following table:

Fraction of solar radius	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95
Percentage discrepancy	.2	.4	.5	.7	.9	1.2	1.5	2.2	3.8	5.0

In view of what has been said, we conclude that the discrepancy between the true reading and the simultaneous galvanometer deflection is at any rate less than that given above, even for wave-length 0.433μ; is still less for all other wave-lengths observed; and on account of the nearly exactly compensating negative discrepancy for the preceding limb of the sun, that the error in the final result produced by lag of the galvanometer is wholly negligible (compared with other kinds of error) for all wave-lengths.

3. PROPORTIONALITY BETWEEN RADIATION AND DEFLECTION.

It has been shown by several observers that when a change of current is produced in a galvanometer by a very small change in radiation falling upon a bolometer, the change of current produced is almost exactly proportional to the intensity of the radiation which produces it. There is no certainty, however, that the deflection of a given galvanometer needle is proportional to the current which produces it, and we have therefore made the following determination of the ratio of deflection to current for the galvanometer employed at Washington for all bolographic work since the year 1900. The time of single vibration was 2 seconds, or about 0.5 second greater than that usually employed. In this condition a deflection 4.5×10^{-9} ampere produced 1 millimeter deflection on a scale at 1 meter. The results indicating departures from exact proportionality between current and deflection are based on deflections of less than 165 millimeters, which is about the maximum deflection ordinarily employed in bolographic work. The ratios of deflection to current are given in arbitrary units, and are the mean results of 5 determinations in each case.

Deflection	*mm.* 28.0	*mm.* 57.4	*mm.* 84.2	*mm.* 111.3	*mm.* 137.9	*mm.* 164.3	*mm.* 190.2	*mm.* 215.7	*mm.* 240.1	Mean first 6 ratios.
$\frac{\text{Deflection}}{\text{Current}}$	2,806	2,882	2,824	2,805	2,786	2,772	2,756	2,739	2,715	2,812
Percentage deviation from mean.	−0.2	+2.4	+0.4	−0.2	−0.9	−1.4	−2.0	−2.7	−3.6	

We conclude that for the deflection ordinarily employed in bolographic work (i. e., from 50 to 150 millimeters) no correction to the galvanometer scale is necessary in view of the magnitudes of errors from other sources.

4. DEFECTS OF THE SOLAR IMAGE, SKY RADIATION, AND OTHER SOURCES OF ERROR.

As already stated, the image of the sun produced near midday by a reflecting telescope is never as perfect as desired, owing to the warping of mirrors by solar heating, and to the "boiling" introduced by the heating of the air. It is possible that our solar image has been so much affected at times by these defects that errors of appreciable magnitude have thereby been introduced in the results, especially prior to May 11, 1906, when the width of the drift curve was not computed from the Ephemeris, but only observed from the drift curve. It is believed that this source of error since that date has been generally negligible for observations less than 95 per cent of the radius distant from the center of the solar disk.

The tendency of defects in the solar image is to increase the sun's apparent diameter and to produce a more rapid rate of decrease in the intensity of the radiation toward the limb than the true distribution of radiation warrants. Such defects are of rapidly decreasing importance toward the center of the image, because the rate of change of intensity is there so slow that the confusion of the radiation from a considerable area would produce little change of intensity. If it were possible to obtain a satisfactorily accurate etimate of the sun's condition by observations restricted to the inner half of the radius of the disk, the defects of our solar image would doubtless at all times be negligible, provided the positions along the radius were computed from the Ephemeris and the clock rate and not from the apparent width of the record; but the variations of atmospheric transmission and the disturbances of the bolometric apparatus prevent such a great reduction of the field of observation as this.

It is not possible to discover exactly how much of error in our results is to be attributed to defects in the solar image. One way of approaching the question is by comparing the width of the bolographic records with the computed widths corresponding to the time required for the solar image to cross a given meridian; but this confuses the effects of sky radiation, radiation of the corona and chromosphere, defects of the solar image, diffraction, width of slit, sluggishness of the bolometric apparatus, and other things, all tending to make the bolometric record of greater width than its computed value. Before discussing these things further we will give a series of measurements intended to show the combined effect of them all upon the bolometric record. In Table 42 the numbers give the intensity of energy near the limb in terms of the intensity at the center of the disk for light of two given wave-lengths as observed on May 14, 1907. The distances from the center are expressed in fractions of the radius of the disk as computed from data given in the American Ephemeris.

TABLE 42.—*Form of drift-curves near the solar limb.*

May 14, 1907.	Intensity.			
Distance from center.	Wave-length 0.46μ.		Wave-length 1.03μ.	
	Advancing limb.	Following limb.	Advancing limb.	Following limb.
1.040	0.000	0.000	0.000	0.007
35	.000	.000	.000	.008
30	.002	.000	.000	.010
25	.004	.000	.000	.014
20	.007	.001	.000	.019
15	.011	.003	.001	.026
10	.018	.012	.012	.036
05	.036	.031	.066	.051
1.000	.062	.053	.155	.086
0.995	.103	.103	.317	.284
90	.156	.172	.482	.517
85	.226	.236	.596	.614
80	.288	.283	.649	.667
75	.332	.319	.676	.681
70	.479	.356	.689	.693
65	.406	.394	.699	.700
60	.432	.407	.710	.706

Computed linear width of record, 8.87 centimeters.
Measured height at maximum:
$\lambda=0.46\mu$, 5.35 centimeters.
$\lambda=1.03\mu$, 13.80 centimeters.
Limit of accuracy of single observation of intensity given in table:
$\lambda=0.46\mu$, 0.01.
$\lambda=1.03\mu$, 0.005.

From the measurements just given it appears that at wave-length 0.46μ the agreement in form of the curve, as between the advancing and following limbs of the disk, is within the error of the observation. The principal cause of the small differences noted, which are seldom of the order of 1 millimeter as measured on the plate, is the instability of the galvanometer zero, and consequent uncertainty as to the exact zero of intensity on the plate. From the measurements at wave-length 1.03μ there appears to be a well-marked difference at and beyond the limb between the records of the advancing and following sides. This is attributable to the sluggishness of the bolometer in coming to a steady state of temperature, and is often noted when a very sudden and large change of the intensity of incident radiation has occurred. Only about four seconds in fact elapse between readings at 52 per cent and 1 per cent of the maximum, respectively, and during a part of this time there is a very appreciable amount of radiation received, so that the actual time required by the bolometer to achieve a practically steady state is very short.

Comparing the two records of different wave-lengths, we find that while both exhibit energy at the computed limb of the sun, this is on the average less than 9 per cent as intense as that at the center, and in both records substantially disappears at a distance of one one-hundredth of a radius outside the limb. The steeper sided record (for wave-length 1.03μ) shows the greater proportion of energy outside, inclining us to infer that the energy there is scattered principally by diffraction and optical defects of the telescope, and not by the air; for, as is well known, the longer waves are less sharply focussed by a telescope, though very much less strongly scattered by the air.

Julius has drawn attention to the solar radiation scattered by the sky as a source of error in measurements like ours, but the following considerations seem to show that this error is negligible. As stated already, we are accustomed to continue the exposure of the apparatus to the sky for a minute or more before and after exposing to the sun, and to insert a shutter to cut off the light entirely for a few seconds at about the middle of the interval covered by the sun exposure. From the examination of numerous records it appears that the total deflection produced by the sky radiation and all other causes combined, at or beyond 1.5 per cent of the radius outside the computed width of the disk, is certainly less than 1 per cent of the deflection at the center of the disk. The deflection at a point 1 per cent of the radius within the computed limb of the disk is from 20 to 50 per cent of the deflection at the center of the disk, depending on the wave-length of the light. From this it follows that the total intensity of scattering at a distance of 2½ per cent of the radius from a given point on the disk is at any rate of less than one-twentieth the intensity at the point itself; but the greater portion of the deflection observed outside the computed boundary is attributable to diffraction, "boiling", tremor, and other defects of the image rather than to sky radiation.

If, in fact, sky radiation was of consequence, it would be more prominently noticeable for short wave-lengths than for long, and for Washington observations than for those on Mount Wilson; but the distribution of intensity outside the computed image is practically the same for short wave-lengths as for long, and the results obtained on Mount Wilson are, as will be shown in Chapter III, in very close agreement with those obtained in Washington. In short, we can discover no indication that sky radiation is of any consequence as a source of error in our work.

5. CLOCK RATE.

The following table shows the changes in the values of the "solar transmission coefficients" which would be caused by a change of 1 per cent in the computed width of the drift record. The table covers the range of values found in our experiments.

Value of coefficient	0.425	0.500	0.575	0.625	0.700	0.800	0.850
Change for width error of 1 per cent	.029	.027	.025	.023	.019	.014	.011

From this table it can be seen that the clock rate should be known to within about 0.2 per cent to insure an accuracy of about 1 per cent in the "solar transmission coefficients" for the shorter wave-lengths examined.

This requirement seems to be fulfilled in our recent work, as shown by the agreement of the values of the clock rate determined for numerous days of observation and expressed in terms of the movement of the photographic plate per minute. The numbers range from 3.96 to 3.98 centimeters per minute, but with few exceptions fall within a range of 1 part in 400.

SUMMARY OF DISCUSSION OF SOURCES OF ERROR.

(1) It appears that there is no probability that the form of the energy curves is altered appreciably by reason of the fact that the galvanometer does not respond instantly to the full influence of the changes of radiation; so that no disadvantage seems to attend the method employed of allowing the solar image to drift over the spectrobolometer slit.

(2) Variations of atmospheric transparency are doubtless prejudicial, but their effects are diminished by making several independent "drifts" at each wave-length examined on each day of observation.

(3) Blurring of the image by "boiling," warping of the mirrors, stray light, etc., was undoubtedly a variable and dangerous source of error prior to May 11, 1906, because it affected the widths of the records, and hence the computed positions on the disk. Since May 11, 1906, the width of the records has been usually computed from the American Ephemeris and a clock rate determined on each day of observation, and in these conditions the blurring of the image is thought to be generally negligible as a source of error. Sky light appears to be of no measurable importance as a source of error.

Chapter III.

RESULTS OF OBSERVATIONS OF THE BRIGHTNESS OF THE SOLAR DISK.

SPECIMEN OBSERVATIONS.

On May 14, 1907, with light of the wave-length 0.503μ falling upon the bolometer, a solar intensity curve was produced in the manner described in Chapter II. For the plate which was used to record this bolometric observation the rate of movement was determined to be 3.980 centimeters per minute. The sidereal time required for the sun's semidiameter to cross the meridian is given by the American Ephemeris at $1^{m}\ 7^{s}.03$. Hence, the width computed for the record is 8.876 centimeters.[1] The following pairs of measurements on the preceding and following limbs were made at various distances from the center of the record to determine the form of the intensity curve.

	cm.	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*
Height {	11.10	10.95	10.46	9.88	9.22	8.88	8.52	8.05	7.56	6.72	6.23	5.70
Height {	......	11.05	10.38	10.00	9.30	8.92	8.59	8.12	7.50	6.85	6.37	5.80
Distance from center	0.00	1.00	2.00	2.50	3.00	3.20	3.40	3.60	3.80	4.00	4.10	4.20

In accordance with the graphical process explained in Chapter II, the following data were plotted:

Log. height {	1.0453	1.0395	1.0195	0.9948	0.9647	0.9484	0.9304	0.9058	0.8785	0.8274	0.7945	0.7559
Log. height {	....	1.0433	1.0161	1.0000	.9685	.9504	.9340	.9096	.8751	.8357	.8041	.7634
Function of distance from center[1]	1.000	1.021	1.094	1.161	1.268	1.323	1.390	1.480	1.602	1.767	1.882	2.024

[1] $\text{Function} = 4.76\left\{\sqrt{(1.21)^2 - \frac{\rho^2}{R^2}} - \sqrt{(1.00)^2 - \frac{\rho^2}{R^2}}\right\}$. See Chapter II.

The tangent of the inclination of the best straight line thus determined is -0.271, which is the logarithm of the "transmission coefficient," and the "transmission coefficient" itself is 0.536.

[1] Allowance is made for the difference between mean and sidereal time.

Performing the reduction of the data according to the other method explained in Chapter II, we find the following difference between the logarithms of heights at the center of the drift curve and the heights at certain distances from the center of the curve. The values given are interpolated from the logarithmic plots by taking the mean of the values for the preceding and following limbs.

△ Log. height	0.000	0.0593	0.1163	0.1688	0.2233	0.2783
Distance from center (fraction of radius)	.000	.614	.774	.857	.908	.942

In accordance with the mean results of many measurements near the center of the disk it appears that local irregularity of the record under examination requires a correction of −0.0049 to be applied to the logarithm of the height of the curve at its center. Applying this correction we obtain the following mean results:

Log. intensity	0.0049	9.9456	9.8886	9.8361	9.7816	9.7266
Intensity	1.011	.8822	.7738	.6857	.6047	.5328
Distance from center (fraction of radius)	.000	.614	.774	.857	.908	.942

SUMMARY OF RESULTS BY FIRST METHOD.

From ninety-five days of observation, all reduced by the first method of procedure, the following mean values of the tangent of inclination of the representative straight lines resulting from the graphical process have been computed:

Wave-length.	0.40μ.	0.45μ.	0.50μ.	0.60μ.	0.70μ.	0.80μ.	0.90μ.	1.00μ.	1.20μ.	1.60μ.	2.00μ.	Mean.
Transmission coefficient ($\log^{-1}\tan\theta$.)	.468	.496	.538	.616	.659	.699	.723	.742	.771	.812	.846	.670

The following Table 43 is a summary of the work done since June, 1905, giving the average departures from the above mean values for the mean results of the separate days of observation. The results obtained prior to June, 1905, may be found in the Smithsonian Report for 1905, but they are not strictly comparable with those given here, because the assumption as to the proper width to use in the reductions differed from that now made.

TABLE 43.—*Summary of results of solar drift curve observations.*

DEVIATIONS FROM MEAN TRANSMISSION COEFFICIENTS.

Date.	Grade.	0.40μ.	0.45μ.	0.50μ.	0.60μ.	0.70μ.	0.80μ.	0.90μ.	1.00μ.	1.20μ.	1.60μ.	2.00μ.	Mean.
1905.													
June 29	?	....	....	−0.016	−0.014	−0.007	−0.012	....	....	....	....	....	−0.012
July 10	?	....	....	−.009	....	−.008	....	....	....	....	....	....	−.008
15	e. ?	−.018	−.026	−.019	−.023	−.022	−.019	−.014	−.014	−.014	−.012	−.007	−.017
17	v. g.	−.023	−.043	−.029	−.028	−.017	−.019	−.019	−.014	−.009	−.010	−.007	−.020
18	g.	....	−.020	−.013	−.019	−.009	−.011	−.011	−.011	−.007	....	....	−.013
25	p.	....	....	−.004	−.009	−.003	−.009	−.009	−.009	....	....	....	−.007
26	e.	−.018	−.021	−.014	−.015	−.008	−.014	−.014	−.014	−.009	−.010	−.007	−.013
Aug. 3	g.	....	....	+.001	−.009	+.002	....	....	....	....	....	....	−.002
4	e.	+.007	−.011	+.001	−.009	+.002	−.004	−.004	−.004	−.009	−.007	−.002	−.004
17	g.	....	−.026	+.001	+.011	+.016	....	−.019	....	....	....	....	−.003
21	g.	....	....	+.001	−.004	+.002	−.009	−.004	−.009	−.004	−.007	+.002	−.004
22	g.	....	....	−.014	−.014	−.008	−.009	−.019	....	....	....	....	−.013
Sept. 1	p.	....	....	+.030	+.030	....	....	....	....	....	....	....	+.030
5	?	....	....	−.014	−.014	−.008	....	....	....	....	....	....	−.012
7	g.	....	....	−.009	−.009	+.002	−.001	+.001	−.004	+.001	−.002	+.002	−.002
9	?	....	....	+.003	−.004	+.002	−.004	−.009	....	....	....	....	−.002
13	?	....	....	....	−.009	−.008	−.014	−.014	−.018	....	....	....	−.013
26	?	....	−.016	−.014	−.018	−.008	−.014	−.014	−.009	−.008	−.012	−.007	−.012
27	v. g.	....	−.031	−.029	−.035	−.024	−.027	−.022	−.017	−.014	−.007	−.004	−.021
28	e	....	....	−.033	−.038	−.033	−.034	−.029	....	....	....	....	−.033
30	?	....	....	−.007	−.006	−.004	−.010	−.005	−.005	−.004	....	....	−.006
Oct. 5	?	....	−.011	−.006	−.004	+.002	−.004	−.004	−.004	−.008	−.007	+.002	−.004
7	v. g.	+.055	−.018	−.005	−.005	−.004	−.009	−.009	−.009	....	....	....	.000
9	e.	+.006	−.017	−.010	−.005	+.001	−.005	−.005	−.005	.000	−.007	+.001	−.004
13	e.[2]	−.027	+.003	.000	+.002	+.006	−.006	−.002	−.003	.000	−.004	−.002	−.003
16	v. g.	....	+.004	+.006	+.006	+.012	+.006	+.001	+.001	−.008	−.007	−.007	+.001
Nov. 1	e.	....	....	+.011	−.010	−.002	−.005	−.001	.000	+.001	....	....	−.001
2	e.	....	−.003	+.009	+.009	+.014	+.003	+.003	−.002	−.002	−.010	−.006	+.002
4	e.	....	−.016	+.006	+.006	+.016	+.005	+.006	+.001	−.004	−.002	....	+.002
10	p.	....	....	+.031	+.029	+.032	....	....	....	....	....	....	+.031
11	e.	....	....	+.016	+.017	+.002	+.001	+.001	+.004	+.004	−.002	....	+.005
14	e.	....	+.004	+.001	−.015	−.028	−.029	−.027	−.020	−.010	+.018	....	−.012
17	?	....	+.004	−.007	−.017	−.026	−.021	−.019	−.016	−.011	−.001	....	−.013
21	v. g.	....	....	−.006	−.006	−.003	+.001	+.009	+.006	+.005	−.002	−.005	.000
22	v. g.	....	....	−.009	−.008	−.003	−.004	+.001	+.004	.000	−.002	....	−.003
Dec. 5	e.	....	....	+.037	+.036	+.021	+.011	+.019	+.019	....	....	....	+.024
7	g.	....	....	−.010	+.003	+.002	+.015	+.015	+.016	+.014	+.010	+.012	+.009
11	e.	....	....	....	−.017	−.015	−.004	−.003	+.002	+.007	+.013	+.016	.000
22	v. g.+	....	....	....	....	−.009	−.002	−.002	−.005	−.004	−.005	....	−.004
26	v. g.	....	....	−.014	−.011	−.002	−.009	−.009	−.013	−.013	....	....	−.010
30	v. g.	....	....	−.024	−.014	−.012	−.018	−.018	−.022	−.027	−.029	−.020	−.020
1906.													
Jan. 5	e.	....	....	+.014	+.012	+.016	+.009	+.004	....	....	....	....	+.011
6	e.	....	....	−.013	−.012	−.020	−.006	−.009	....	....	....	....	−.012
9	g.	....	....	−.014	−.009	+.006	.000	−.004	−.004	−.009	−.012	−.012	−.006
24	e. ?	....	....	−.016	....	....	....	....	....	....	....	....	−.016
30	e.	+.052	−.006	−.015	−.015	−.001	−.003	−.002	−.001	−.006	....	....	.000
Feb. 3	v. g.	....	+.018	+.023	+.008	.000	....	....	....	....	....	....	+.012
6	e.	....	+.001	+.015	+.004	+.003	+.006	+.002	+.001	−.002	−.002	+.001	+.003
14	v. g.	....	....	−.003	−.004	−.010	+.006	.000	+.003	....	....	....	−.001
15	v. g.	....	+.001	+.006	+,004	−.004	+.009	+.007	+.005	+.006	+.006	+.014	+.005
20	e.	....	....	....	+.002	−.003	+.011	+.013	+.017	....	....	....	+.008
23	e.	....	−.002	−.015	+.015	−.008	−.004	−.005	−.005	+.002	+.013	−.005	−.001
26	e.	....	+.029	−.018	−.007	−.009	+.008	+.007	+.011	+.012	+.022	+.008	+.006
Mar. 6	v. g.	....	+.009	+.011	+.021	−.001	+.007	+.003	+.001	+.003	....	....	+.007
22	e.−	....	....	+.003	+.012	+.002	+.009	+.006	+.004	.000	−.005	+.009	+.004
23	g.+	....	....	−.027	−.003	−.008	−.001	−.004	−.003	−.004	−.005	+.007	−.005
Apr. 12	g.+	....	....	+.023	+.012	+.011	....	....	....	....	....	....	+.015
19	v. g.	....	+.025	+.013	+.007	−.001	+.009	+.009	+.010	−.001	−.003	+.004	+.007
May 8	e.	....	....	+.008	+.011	+.022	+.017	+.018	....	....	....	....	+.015
11	v. g.	....	+.001	+.011	....	....	....	....	....	....	....	....	+.006
17	e.	....	−.004	−.001	−.005	−.015	−.015	−.019	−.018	−.017	−.013	−.004	−.011
18	p.	....	+.001	+.009	.000	+.007	−.004	−.008	−.007	−.012	−.013	+.001	−.003

TABLE 43.—*Summary of results of solar drift curve observations*—Continued.

DEVIATIONS FROM MEAN TRANSMISSION COEFFICIENTS—Continued.

Date.	Grade.	0.40μ.	0.45μ.	0.50μ.	0.60μ.	0.70μ.	0.80μ.	0.90μ.	1.00μ.	1.20μ.	1.60μ.	2.00μ.	Mean.
1906.													
May 21	e.	....	+.006	+.021	+.021	+.014	+.016	+.013	+.011	+.010	+.009	+.006	+.013
23	e.	....	+.011	+.006	+.008	−.003	+.006	+.005	+.006	+.004	+.003	+.009	+.006
24	e.	....	+.010	+.028	+.015	+.021	+.028	+.027	....	....	....	....	+.022
25	v.g.	....	+.016	+.039	+.015	+.010	+.017	+.017	....	....	....	....	+.019
29	g.	....	+.031	−.021	−.005	−.003	+.013	+.013	+.013	+.011	+.012	+.006	+.007
June 22	e.	....	+.003	+.003	−.003	....	....	....	....	....	....	....	+.001
25	v.g. ?	....	+.012	+.020	+.008	....	....	....	....	....	....	....	+.013
29	e.	....	+.011	+.026	+.010	+.002	+.002	.000	−.002	−.008	−.011	−.012	+.002
Aug. 31	g.	....	+.007	−.006	+.005	+.004	+.014	....	....	....	....	....	+.005
Sept. 1	e.	....	−.003	−.007	−.003	−.008	−.001	−.001	+.002	+.002	+.004	+.006	−.001
7	e.	....	−.019	.000	+.008	+.019	+.011	+.010	....	....	....	....	+.005
8	g.	....	−.010	+.003	....	....	+.012	+.015	+.013	+.012	+.016	....	+.009
19	g.+	....	+.021	+.016	+.002	....	....	....	....	....	....	....	+.013
21	g.	....	....	+.001	−.001	−.011	....	....	....	....	....	....	−.004
25	v.g.−	....	....	−.001	−.004	+.008	+.026	+.012	+.013	+.013	....	....	+.010
Oct. 5	v.g.	....	....	−.004	....	....	....	....	....	....	....	....	−.004
11	v.g.	....	+.061	−.021	+.030	−.003	....	....	....	....	....	....	+.017
12	e.	....	....	−.006	.000	−.014	−.005	−.005	−.004	−.004	....	....	−.005
15	e.	....	....	+.007	+.014	....	....	....	....	+.018	+.005	−.001	+.009
Nov. 1	g.	....	....	−.015	−.006	−.008	....	....	....	....	....	....	−.010
2	e.	....	....	+.019	+.016	+.010	+.017	+.013	+.012	+.008	+.010	+.004	+.012
3	v.g.−	....	....	−.006	+.007	−.004	+.006	....	....	....	....	....	+.001
6	v.g.	....	−.009	+.009	....	....	....	....	....	....	....	....	.000
7	v.g.−	....	....	−.011	−.004	+.003	−.003	−.002	+.001	−.004	−.002	+.001	−.002
16	?	....	....	−.021	−.014	+.007	+.006	+.013	+.019	+.026	+.035	....	+.009
22	e.	....	+.011	+.020	+.011	+.013	....	....	....	....	....	....	+.014
27	e.−	....	+.023	+.028	+.014	+.011	+.012	+.015	+.012	+.002	....	....	+.015
Dec. 4	g.+	−.030	−.009	+.012	....	....	....	....	....	....	....	....	−.009
12	g.	....	....	+.013	....	....	....	....	....	....	....	....	+.013
26	e.	....	....	+.005	+.004	+.007	+.012	+.011	+.018	+.025	....	....	+.012
1907.													
Feb. 15	e.	....	+.011	+.011	+,028	+.027	+.021	+.019	+.019	+.018	+.015	....	+.019
May 13	e.	....	−.011	+.020	+.028	+.033	+.030	+.030	+.034	+.036	....	....	+.025
14	e.	....	−.023	−.007	−.005	−.004	−.010	−.006	−.006	−.002	+.004	+.007	−.005
Mean deviations.	....	.0251	.0141	.0127	.0115	.0096	.0104	.0100	.0091	.0085	.0092	.0063	.0091
Mean percentage deviations....	....	5.4	2.8	2.4	1.9	1.5	1.5	1.4	1.2	1.1	1.1	0.7	1.4

EVIDENCE OF THE VARIABILITY OF TRANSMISSION IN THE SOLAR ENVELOPE.

Referring to Chapter I of Part III, our knowledge of the solar condition is so imperfect that we hardly know what we ought to expect of a series of measurements like that just given. We do not know what produces the phenomenon of apparently varying brightness over the sun's disk, nor what change, if any, in the distribution of brightness should accompany a change in the intensity of solar radiation. It is conceivable, for instance, that an increase of absorption, or scattering, might occur in the solar envelope without at all changing the gradation of brightness from the center of the solar disk to the limb, for such a change might simply reduce the radiation from every part by a constant proportion. This state of affairs seems hardly probable, but we have no reason at all to suppose that a fractional change of the values we have called "transmission coefficients" would of necessity occur in equal magnitude with a fractional change in the "solar-constant" values. The fractional change in "transmission coefficients" might be, we affirm, of any rate in its magnitude from zero to unity, or beyond, as compared with a change of the "solar constant," without contradicting any knowledge we have on the subject.

The average deviations of the "transmission coefficients," as given at the bottom of Table 43, increase steadily, both in actual magnitude and in percentage, with decreasing wave-length. This result might be a consequence of error in determining the width corresponding to the sun's diameter, but it is of the same kind which would be expected if there was a real change in the sun. As has been stated, there is an error of uncertain and variable magnitude likely to be present in the results of observations prior to May 11, 1906, owing to the fact that the width of the "drift curves," as measured on the plates, formed the basis of reduction in abscissæ, and not the computed width depending on an ephemeris of the sun and the rate of motion of the plate, as in the subsequent work. But if we confine our attention wholly to that part of Table 43 which includes days later than May 11, 1906, we find several days of deviations so large as to require ± 1 per cent or more change from the computed width of the record to account for the departures on the basis of accidental error; so that there is a range of 2 per cent or more in width to be accounted for as due to errors of clock rates, if we deny that the changes are really solar. Referring to Chapter II, clock errors of this magnitude are highly improbable.

The magnitudes of the separate deviations given in Table 43 are generally very small, and are hardly greater, as a rule, than the errors to be expected from accidental causes, so that if the "transmission coefficients" were really what their name implies, we should conclude that there had been very little change in solar-radiation since July, 1905. But, as we have stated above, this conclusion is not well warranted, because we are ignorant of the solar conditions which cause the phenomena observed. Referring to the last vertical column of Table 43, it will be seen that the separate days of observation do, however, consistently indicate small differences of the solar transmission. The most marked of the departures, both positive and negative, are compared in the following table with the "solar-constant" values observed nearly simultaneously, as given in Table 14, Part I:

Date.	Dec. 5, 1905.	May 8, 1906.	1907.						1905.					
			May 24.	May 25.	Nov. 27.	Feb. 15.	May 13.	Mean.	July 15.	July 17.	Sept. 27.	Sept. 28.	Dec. 30.	Mean.
Solar-transmission departures	+.024	+.015	+.022	+.019	+.015	+.019	+.025	+.020	−.017	−.020	−.021	−.033	−.020	−.022
Grade	e.	e.	e.	v.g.	e.	e.	e.	....	e.?	v.g.	v.g.	e.	v.g.	....
Date	Dec. 4	....	May 24	....	Nov. 22	Feb. 15	May 13	....	July 12	July 19	Sept. 27	....	....	....
"Solar-constant" values	*2.036	....	*2.157	....	*2.046	*1.972	*2.119	*2.066	†2.03	†2.09	†2.00	....	....	†2.04
Grade	v.g.	....	p.	....	v.g.	e.	e.	....	e.	v.g.	e.[2]	....	....	....

* Washington observations. † Mount Wilson observations.

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It is unfortunate that all the positive departures in the table just given must be compared with Washington "solar-constant" observations, for lack of nearly simultaneous observations on Mount Wilson, and that there is often a difference of time of several days between the two kinds of observations. As the results stand, there seems to be a slightly higher mean value of the "solar constant" corresponding to higher values of the "solar transmission." But, as stated in Chapter VI, Part I, Washington values of the "solar constant" appear to run about 3 per cent higher than Mount Wilson values in a number of instances, not, to be sure, of very great weight. If this correction should be applied here, the result noted above would be reversed; so that the comparison does not show conclusively that higher values of the "solar transmission" attend higher values of the "solar constant" of radiation.

MEAN AND EXTREME OBSERVATIONS REPRESENTED BY THE SECOND METHOD.

The solar drift curve observations of August 4 and November 2, 1905, and January 30, February 26, May 17, and September 1, 1906, forming a group together, and those of September 27, 1905, and of November 2, 1906, taken separately, have been reduced by the second method explained in the preceding chapter and illustrated above. The mean result for the first six days may be taken as representing the average condition of the distribution of radiation over the sun's disk in 1905 and 1906, and the last two days' results as representing, respectively, conditions of negative and positive departures from the average conditions.

TABLE 44.—*Distribution of brightness over the solar disk.*

Condition of solar transmission.	Wave-length.	Intensity of radiation at following fractions of radius from center of solar disk.						
		0.000	0.619	0.780	0.863	0.915	0.949	0.972
	μ							
Average	0.433	1,000	839	716	617	539	467	400
September 27	.501	1,000	847	731	633	541	442	414
Average	.501	1,000	886	774	681	602	527	454
November 2	.501	1,000	912	802	711	637	558	480
September 27	.604	1,000	882	787	702	623	511	....
Average	.604	1,000	889	802	728	659	594	530
November 2	.604	1,000	894	802	726	661	602	540
September 27	.866	1,000	917	847	789	730	660	585
Average	.866	1,000	926	863	804	757	710	655
November 2	.866	1,000	926	859	802	747	702	653
Average	2.097	1,000	967	935	907	878	848	813

The differences between solar drift curves for the three conditions shown in the above table are so considerable that no doubt is entertained that there are really changes in the distribution of brightness of the sun's disk from time to time.

It has been known for many years that the contrast between the brightness of the center and limb of the solar disk decreases with increasing wave-length throughout the visible spectrum. The results here presented are confirmatory of this, and show that the contrast continues to dimish for infra-red rays. It would naturally be expected that if the distribution of brightness over the solar disk should be found to alter from time to time, the change would be most rapid if observed with the shorter wave-length rays, and this is apparently the case, as shown by the table just given.

COMPARISON OF WASHINGTON AND MOUNT WILSON SOLAR DRIFT CURVE OBSERVATIONS.

On July 27 and 28, and August 1, 10, and 12, 1905, drift curves were made by C.G.A. and L.R.I., observers on Mount Wilson, employing the Snow telescope of the Carnegie Solar Observatory and the Smithsonian bolometric apparatus. Unfortunately it was not at that time recognized that the width of the record corresponding to the diameter of the solar disk should be determined by means of the plate speed and Ephemeris, and therefore the plate speed was not determined. Accordingly the plates were reduced, as was customary at that time, on the assumption that the measured width of the record between points on the drift curves whose ordinates are 4 per cent of the maximum ordinate, represented the diameter of the solar disk. As given in Table 43, all the Washington work of that period has now been corrected by decreasing the assumed diameters 0.0075, or three-fourths of 1 per cent. This correction has been determined by comparing the computed widths of many recent curves with the measured widths of the same curves as obtained by the old process. This correction increases the Washington "solar transmission coefficients" for wave-length 0.50μ obtained on August 3, 4, and 17, 1905, from 0.520 to 0.539, or nearly 4 per cent. No correction of the kind has been applied to the following values obtained from Mount Wilson data of the dates above given, because it is thought that as the bolometer used there was but one-sixth as wide as that used in Washington, and as the definition of the telescope was presumably better, the proper correction, if any, would probably be much less.

Solar "transmission coefficients" for wave-length 0.50μ obtained from Mount Wilson observations, 1905.

Date.	July 27.	July 28.	Aug. 1.	Aug. 10.	Aug. 12.	Mean.
Coefficient	0.539	0.551	0.537	0.536	0.543	0.541

Referring to the Washington values of August 3, 4, and 17, just given, and in view of what has just been said, any difference which would exist between solar "transmission coefficients" obtained at Washington and Mount Wilson by the most modern processes would certainly be very small indeed.

Mr. Palmer, of the staff of the Carnegie Solar Observatory, made numerous drift curves during the year 1906. From four such curves for the rays of wave-length 0.554μ, which he made on October 8 and 9, 1906, the ratios of intensity at several points on the solar surface have been determined and compared with mean values obtained from Table 44 by interpolation. The results are given in the following table:

Intensity of radiation over the sun's disk at wave-length 0.554μ.

Distance from center	000	0.619	0.780	0.863	0.915	0.949
Palmer	1,000	879	774	690	610	(527)
Abbot and Fowle	1,000	888	791	710	636	566
Deviations	000	−9	−17	−20	−26	−39

The differences are increasingly negative for points nearer and nearer the solar limb. But the column marked "Abbot and Fowle" represents the average condition of the sun for several years, whereas that marked "Palmer" represents the condition on October 8 and 9, 1906. On both October 6 and 9 the "solar-constant" value determined on Mount Wilson was 2.003, as given in Table 14. This value is decidedly lower than the mean value of the "solar constant," so that the condition of the sun was favorable to produce greater contrast between center and edge of the disk than usual, according to other results given in the present chapter, just as in fact appears above.

On the whole, then, we find no reason to suspect any difference due to experimental or atmospheric causes between Washington and Mount Wilson observations of the distribution of brightness over the solar disk.

SUMMARY OF PART III.

The determinations of the distribution of brightness over the sun's disk, which we have described in Part III, seem to fall in very good accord with the conclusion reached in Part I and confirmed in Part II of this volume, namely: The solar radiation is neither constant nor subject only to trifling variations of an eleven-year or other period; but its intensity fluctuates often as much as 5 per cent, and occasionally as much as 10 per cent within a single year, or even month.

We may conjecture the cause of these seemingly nonperiodic fluctuations to be a changing transparency of the outer envelope of the sun. It is probable that the envelope in question is a layer thin relatively to the solar radius, and which may be the so-called reversing layer of the sun. Its function, apart from selectively absorbing the rays emitted by iron and other metallic vapors, is to scatter the rays not selectively absorbed in much the same way that our own atmosphere scatters sunlight. As our own atmosphere is at times more hazy than at others, so it may be with the solar envelope in question. The immediate effect of such a change of transparency of the solar envelope is to decrease the amount of solar radiation, and this decrease is greater for the shorter wave-lengths than for longer ones. A secondary effect of the decrease in solar radiation may be to raise the temperature of the sun and thereby to clear up again the defects of transparency supposed temporarily to exist, thus letting forth the solar radiation in exalted intensity again.

RADIATION OF SUN SPOTS.

On several days in August, 1905, "drift curves" were made on Mount Wilson over sun-spot regions. In these experiments the slit of the spectrobolometer was diminished in height to less than the vertical diameter of the spot in question, so as to fall entirely in the spot image when the latter became central on the slit. The cœlostat employed with the Snow telescope has gearing adapted to follow the moon. This was used, so that the sun spot drifted very slowly over the slit of the spectrobolometer. Under these circumstances 7 bolographic intensity curves were made on August 12, 1905, 2 each at wave-lengths 0.448μ and 2.115μ, and one each at wave-lengths 0.586μ, 0.799μ, and 1.218μ. These curves were each measured at four points corresponding to well-marked details of structure of the spot, and the ratio of the intensity of light in the spot at these points to that of the surrounding photosphere was found to be as follows. The column marked "Distance from spot umbra" serves merely to distinguish relatively the several positions, and is given in arbitrary units.

Distance from spot umbra.	Ratio of intensity in spot to intensity of surrounding photosphere for following wave-lengths.				
	μ 0.448	μ 0.586	μ 0.799	μ 1.218	μ 2.115
—4	.857	.850	.900	.941	....
—2	.492	.686	.783	.842	.897
0	.377	.424	.535	.610	.761
+1	.679	.764	.852	.865	....

These sun-spot results are doubtless all a little too large, because of stray light from the photosphere encroaching upon the spot. They show clearly, however, the great increase in contrast, as the spots are observed in shorter and shorter wave-lengths. This change of contrast is of the same kind as that which has been noticed in the study of the brightness of the solar disk, but we are not prepared to propose an explanation of it.

SUMMARY AND CONCLUSION.

The present volume is an account of the work of the Astrophysical Observatory from 1900 to 1907, with details of the investigations made, the apparatus and methods used, and the results obtained.

Speaking broadly, the investigation relates to the intensity of the rays of the sun and the dependence of the earth's temperature thereon. The subject is treated in three parts: First, the amount of the solar radiation as it would be found if measured outside the earth's atmosphere, at mean solar distance, or, as it is often termed, "the solar constant of radiation;" second, the dependence of the earth's temperature on the amount of solar radiation; third, the difference in brightness between the center and edge of the sun's disk and its relation to the quantity of solar radiation received by the earth.

The work is not limited to a determination of constants of nature, for the possibility was early recognized that the radiation of the sun might be far from uniform, so that the "solar constant of radiation" might prove to be a mean value about which the intensity of the solar beam would be found to fluctuate very perceptibly from time to time. A principal aim of the work has therefore been to prove whether such fluctuations of the quantity of solar rays do exist, and if so what may be the magnitude of the changes, their effects on climate, and their causes. For these purposes the measurement of the intensity of solar radiation and of the distribution of brightness over the disk of the sun have been made as often as possible for several years, and a study of the variation of temperature for the last thirty years at about fifty stations scattered as widely as possible over the inland areas of the world has also been made.

A part of the measurements have been made in Washington, and therefore practically at sea-level, and a part at Mount Wilson in California at about 1,800 meters, or nearly 6,000 feet, elevation. The radiation of the sun has been studied not only in the total but also as dispersed into its spectrum, and not only with regard to the rays visible to the eye but also with regard to the rays whose wave-length is too long or too short to affect the eye. For all these different rays the earth's atmosphere has different degrees of absorption, or of diffuse reflection, and in the course of the work the transparency of the earth's atmosphere for many different rays has been extensively investigated. The reflecting powers of the clouds and the air have been measured, and also the quality of the sky light as regards the relative intensity of its rays of different colors.

We use as our unit of measurement that intensity of radiation which, when fully absorbed for one minute over a square centimeter of area placed at right angles to the ray, would produce heat enough to raise the temperature of a gram of water 1° centigrade. This unit is termed 1 calorie per square centimeter per minute.[1]

The mean result of 130 measurements conducted on Mount Wilson in the summer and autumn months of 1905 and 1906 fixes the intensity of solar radiation outside the atmosphere at mean solar distance as 2.023 calories per square centimeter per minute.

The mean result of 41 measurements at Washington from 1902 to 1907 is 2.061 calories.

It is probable that the mean result of such measurements, if conducted for a long term of years, would be higher, and the probable mean value of the "solar constant" may be estimated in round numbers at 2.1 calories per square centimeter per minute.

Expressed in another way, the solar radiation is capable of melting an ice shell 35 meters (114 feet) thick annually over the whole surface of the earth.

The results of Langley, while seemingly in contradiction of these, in reality support them. For, as he states on page 211 of the Report of the Mount Whitney Expedition, his value (3 calories) for the "solar constant" depends upon an allowance which he made for an apparent "systematic error in high and low sun observations at one station," of such a nature as becomes manifest "by calculating at the lower station, from our high and low sun observations there, the heat which should be found at a certain height in the atmosphere; then actually ascending to this height, and finding the observed heat there conspicuously and systematically greater than the calculated one." As shown in Chapter VII, Part I, of the present volume, this seeming discrepancy arose from a misapprehension of the requirements of the calculations. In fact there is no such systematic error, no correction for it should have been applied by Langley, and the best mean value of his experimental determination of the "solar constant" at Mount Whitney and Lone Pine is 2.14 calories per square centimeter per minute.

Substantial agreement as to the magnitude of the "solar constant" is therefore reached by observations at sea-level, at 1,800 meters, and at 3,500 meters elevation.

The solar radiation is far from being constant in its intensity. The values determined on Mount Wilson range from 1.93 calories to 2.14 calories, and those in Washington from 1.89 calories to 2.22 calories. A change of the intensity of solar radiation of 3½ per cent, due to the decrease in solar distance, occurs from August to October, and this is readily discernible in the work done on Mount Wilson; so that there can be little question that the large changes noted there are really solar changes, and not of atmospheric or accidental origin.

[1]As stated in Chapter II of Part I it is possible that the numerical results given are about 1.5 per cent above what this absolute scale would indicate.

The reality of the supposed solar origin of the changes of radiation observed, is attested by many other evidences stated in Chapter VI, Part I, and Chapter III, Part III.

The temperature of the earth is shown to be in good agreement with the assumed value of the "solar constant," 2.1 calories. Indeed it is shown that unless the albedo, or reflection, of the earth exceeds 37 per cent (a value here determined for it and based on observations at Washington and Mount Wilson), then the mean value of the "solar constant" can not exceed 2.33 calories, else the earth must be a better radiator than the "absolutely black body" or perfect radiator.

It is shown that the surface of the earth can radiate only very slightly to space, on account of the interference of clouds and water vapor to terrestrial radiation; and that the substance which maintains the earth at nearly constant temperature, by emitting to space radiation equal to that received by the sun, is principally the water-vapor layer at 4,000 to 5,000 meters in elevation, whose mean temperature is 10° or more below 0° C.

There is introduced the conception of a "hypothetical earth," similar in dimensions and motions to the real earth, but hollow and like a soap bubble in thickness of wall; perfectly absorbing for solar radiation, and a perfect radiator for long waves; perfectly conducting for heat along parallels of latitude, but perfectly nonconducting along meridians of longitude. The temperature of this "hypothetical earth" is calculated for all times of the year, and for all latitudes, by the aid of the known value of the "solar constant" and the laws of radiation of perfect radiators.

A comparison is made between the annual march of temperature of the "hypothetical earth" and the observed annual march of temperature for 64 stations on the real earth. It is thereby shown that a given fractional change of solar radiation running its cycle in a year produces one-fourth the given fractional change in the absolute temperature of the "hypothetical earth," one-fourteenth of the given fractional change in the temperature of most inland stations, one-twenty-fifth for coast stations, and one-fiftieth for small islands in great oceans. For a fluctuation of 5 per cent in solar radiation, having a period of about a year, there would be produced a change of only about 1° C. in the mean temperature of inland stations, and only about 0°.3 C. for island stations. The effects of more rapid changes of solar radiation would be less readily discernible in their effects on mean temperatures, but may nevertheless be of meteorological importance as promoters of atmospheric circulation.

From a comparison, extending over thirty years, of the temperatures of 47 stations well distributed over the land surface of the earth, it appears possible that changes of solar radiation do produce, not infrequently, well-marked and recognizable changes of temperature over the continental areas of the world. Such changes of temperature would be predictable if accurate measurements of the solar radiation were systematically continued at a few favorable stations.

Numerous measurements of the comparative brightness of the center and edge of the solar disk indicate that the observed changes in solar radiation are attended by a variation of the transparency of the solar envelope, and perhaps are caused by it.

Many results of observations not here enumerated, such as the mean transparency of the upper and lower strata of air, the reflecting power of the clouds, the probable temperature of the sun, and the quality of the radiation of sun spots, will be found set forth both in words and by charts, and also a full description of the apparatus and methods employed for the various kinds of research, and the sources and magnitude of the errors attending their use.

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